University of Alberta

Students' Understandings of Electrochemistry

by

©

Kathryn O'Grady-Morris

A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

Department of Secondary Education

Edmonton, Alberta
Fall 2008

Library and
Archives Canada

Published Heritage
Branch

395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque et
Archives Canada

Direction du
Patrimoine de l'édition

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence
ISBN: 978-0-494-46401-4
Our file Notre référence
ISBN: 978-0-494-46401-4

NOTICE:
The author has granted a non-exclusive license allowing Library and Archives Canada to reproduce, publish, archive, preserve, conserve, communicate to the public by telecommunication or on the Internet, loan, distribute and sell theses worldwide, for commercial or non-commercial purposes, in microform, paper, electronic and/or any other formats.

The author retains copyright ownership and moral rights in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

AVIS:
L'auteur a accordé une licence non exclusive permettant à la Bibliothèque et Archives Canada de reproduire, publier, archiver, sauvegarder, conserver, transmettre au public par télécommunication ou par l'Internet, prêter, distribuer et vendre des thèses partout dans le monde, à des fins commerciales ou autres, sur support microforme, papier, électronique et/ou autres formats.

L'auteur conserve la propriété du droit d'auteur et des droits moraux qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

In compliance with the Canadian Privacy Act some supporting forms may have been removed from this thesis.

While these forms may be included in the document page count, their removal does not represent any loss of content from the thesis.

Conformément à la loi canadienne sur la protection de la vie privée, quelques formulaires secondaires ont été enlevés de cette thèse.

Bien que ces formulaires aient inclus dans la pagination, il n'y aura aucun contenu manquant.

Canada

To David, "mo chuisle"

And to my parents, Jack and Joyce

Whose love and support have made all the difference

ABSTRACT

Electrochemistry is considered by students to be a difficult topic in chemistry. This research was a mixed methods study guided by the research question: At the end of a unit of study, what are students' understandings of electrochemistry? The framework of analysis used for the qualitative and quantitative data collected in this study was comprised of three categories: types of knowledge used in problem solving, levels of representation of knowledge in chemistry (macroscopic, symbolic, and particulate), and alternative conceptions. Although individually each of the three categories has been reported in previous studies, the contribution of this study is the inter-relationships among them. Semi-structured, task-based interviews were conducted while students were setting up and operating electrochemical cells in the laboratory, and a two-tiered, multiple-choice diagnostic instrument was designed to identify alternative conceptions that students held at the end of the unit.

For familiar problems, those involving routine voltaic cells, students used a working-forwards problem-solving strategy, two or three levels of representation of knowledge during explanations, scored higher on both procedural and conceptual knowledge questions in the diagnostic instrument, and held fewer alternative conceptions related to the operation of these cells.

For less familiar problems, those involving non-routine voltaic cells and electrolytic cells, students approached problem-solving with procedural knowledge, used only one level of representation of knowledge when explaining the operation of these cells, scored higher

on procedural knowledge than conceptual knowledge questions in the diagnostic instrument, and held a greater number of alternative conceptions.

Decision routines that involved memorized formulas and procedures were used to solve both quantitative and qualitative problems and the main source of alternative conceptions in this study was the overgeneralization of theory related to the particulate level of representation of knowledge.

The findings from this study may contribute further to our understanding of students' conceptions in electrochemistry. Furthermore, understanding the influence of the three categories in the framework of analysis and their inter-relationships on how students make sense of this field may result in a better understanding of classroom practice that could promote the acquisition of conceptual knowledge – knowledge that is "rich in relationships".

ACKNOWLEDGEMENTS

I would like to thank Dr. Norma Nocente at the University of Alberta for all her guidance throughout the project and graduate studies as I have benefited from her years of experience and expertise in science education.

My thanks go to both Dr. Susan Barker and Dr. Jacqueline Leighton for contributing to my supervisory committee. Their individual knowledge and insightful questions challenged the dissertation process and strengthened the outcome.

Doctoral studies require a significant time commitment and unfailing dedication. Over the past four years, my family and friends have been supportive and understanding of the implications of my undertaking. I am thankful for their patience and encouragement.

I wish to acknowledge the high school teachers and university and college professors that I have had the opportunity to work with and learn from. Thank you for the great things you do for children.

It was the dedication of teachers striving to improve their practice that inspired this study.

And to David. For nodding and smiling along while I talked out ideas and concepts. Thank you for being there with me through this and encouraging me to continue on.

TABLE OF CONTENTS

Chapter Page

I THE PROBLEM

Introduction 1

Beginning my Story 2

Study Overview 11

Statement of Purpose and Research Question 12

Significance of the Research 12

Definition of Terms 14

Research Ethics 16

Interpretation and Representation 16

Delimitations of the Study 17

Limitations of the Study 19

Assumptions 20

Summary of the Forthcoming Chapters 21

II REVIEW OF RELATED LITERATURE

Introduction 23

Research Project Overview 24

Theoretical Background 25

Constructivist Paradigm 25

  Personal Constructivism 27

  Social Constructivism 29

Constructivist Perspective and Learning 30
Framework of Analysis Categories 35
Category I. Types of Knowledge Used in Problem Solving 35
Procedural Knowledge 35
Conceptual Knowledge 36
Definitions of Knowledge Used in This Study 37
Problem-Solving Strategies 40
Category II. Levels of Representation of Knowledge 44
Category III. Alternative conceptions 45
Alternative Conception Research 46
Alternative Conception Research in Electrochemistry 49
Diagnostic Instruments 52
Summary 53

III RESEARCH PROCEDURES
Research Perspective 55
Introduction 55
Pilot Study 59
Development of the Pilot Diagnostic Instrument 60
Student Interview Format 65
Main Research Study 67
The Research Sites 68
The Students 69

The Teachers 70

Classroom Observation 71

Diagnostic Instrument 74

Changes to the Main Study Diagnostic Instrument Resulting from the Pilot Study 75

Changes to the Main Study Interview Protocol Resulting from the Pilot Study 82

Main Study Diagnostic Instrument 84

Format of Student Interviews 87

Pre-interview Activity 87

Task-based Interviews 88

Diagnostic Test Interviews 95

Teacher Group Interview 96

Data Analysis 97

Content analysis of the student textbook 100

Validation of Data 104

IV DATA ANALYSIS AND DISCUSSION

Introduction 107

Category I: Types of Knowledge Used in Problem Solving 109

Overview of Category I Analysis 109

Procedural v Conceptual Knowledge 110

Questions with Higher Conceptual Knowledge Scores 112

Quantitative Decision Routines 114

Qualitative Decision Routines 127
  Using the Redox Table 129
  Calculating Cell Potential 137
  Routine Voltaic Cells 139
  Probing Conceptual Knowledge – Non-routine Voltaic Cells 141
    The Salt Bridge 142
    The Function of the Oxidizing Agent 143
    Electrolytic Cells 144
    Inert Electrodes in Electrolytic Cells 150
    Problem-Solving Strategies in Electrolytic Cells 152
Category II: Levels of Representation of Knowledge in Chemistry 161
  Overview of Category II Analysis 161
  Students' Explanations of Voltaic Cells 169
Category III: Alternative Conceptions 171
  Overview of Category III Analysis 171
  Complete Circuits and Movement of Charged Particles 172
  Probing Conceptual Knowledge with Non-Routine Voltaic Cells 183
    Electrode Characteristics 186
    Everyday Meanings for Scientific Vocabulary 194
      Barrier to Movement 194
      Reversible Reactions 195
      Polarity 195
  Redox Reactions 197

Redox Table 201

Additional Alternative Conceptions Identified During Student Interviews 203

Electric Circuits and Current 204

Voltaic Cells 204

Electrolytic Cells 205

Electrical Neutrality 205

Confronting Alternative Conceptions 208

Summary 211

V CONCLUSIONS AND SUGGESTIONS FOR TEACHING

Overview of the Study 213

Category I: Types of Knowledge Used in Problem Solving 215

Quantitative Decision Routines 220

Qualitative Decision Routines 221

Decision Routines: Recommendations for Teaching 220

Category II: Levels of Representation of Knowledge in Chemistry 222

Category III: Alternative Conceptions 224

Additional Alternative Conceptions Identified 225

Sources of Alternative Conceptions 226

Promoting Conceptual Knowledge Development 227

Use of the Diagnostic Instrument 228

Recommendations for Teaching 229

Limitations of the Study 235

Suggestions for Further Study 236

Final Words 238

REFERENCES 240

APPENDICES

A Electrochemistry concepts 262

B Diagnostic instrument used in pilot study 266

C Diagnostic instrument used in the main research study 278

D Alternative conceptions in electrochemistry 289

LIST OF TABLES

2-1 An excerpt from the *Chemistry 30 Data Booklet* table of standard electrode potentials, also known as the redox table 33

3-1 Quantitative and qualitative methods of data collection and types of data 58

3-2 Time line for research 59

3-3 Source of tier one questions for the pilot study diagnostic instrument 61

3-4 Alternative conceptions used to develop the distractors for question 3-2 for the pilot study diagnostic instrument. 64

3-5 Cross-tabulation analysis table for two-tiered question 3 in the pilot study diagnostic instrument 64

3-6 Scoring scheme for responses on the open-ended questions in the pilot study diagnostic instrument 65

3-7 Sample interview questions used for questions 4-1 and 4-2 in the pilot study diagnostic instrument 67

3-8 Years of teaching experience for teachers involved in this research study 70

3-9 Summary of lesson topics and activities during classroom observations 73

3-10 Summary of learning and instructional materials collected during the study 74

3-11 Description of how the questions used in the main study diagnostic instrument were changed from questions in the pilot study diagnostic instrument 76

3-12 Cross-tabulation analysis of question 4 in the pilot study diagnostic instrument related to a voltaic cell 79

3-13 Cross-tabulation analysis of question 2 in the pilot study diagnostic instrument related to the reduction half-reaction table 81

3-14 Table used for the cross-tabulation analysis of the aggregated data for questions 5-1 and 5-2 in the main study diagnostic instrument with a description of the alternative conceptions used to develop the distractors 87

3-15 A selection of pre-interview activities 88

3-16 Materials and equipment available for student use during the task-based interviews about voltaic and electrolytic cells 89

3-17 Sample interview questions about approaches to solving problems using the pre-interview activity. 90

3-18 Laboratory instructions for the semi-structured, task-based interviews 93

3-19 Sample interview questions during the task-based, semi-structured interviews during which students set up voltaic and electrolytic cells and made predictions and observations about their operation 94

3-20 Sample interview questions used to probe student problem-solving strategies and alternative conceptions for the main study diagnostic instrument interview 95

3-21 Sample interview questions for the teacher group interview 96

3-22 Coding scheme and worksheet for the three levels of knowledge representation for the POE framework during the task-based interview 99

3-23 Coding schemes used to analyze two themes in the student textbook, *Nelson Chemistry* (2003) 101

3-24 Questions used during analysis to identify themes and patterns in the data 103

4-1 Aggregated results of the main study diagnostic instrument 110

4-2 Analysis of numerical response answers to question 7 in the pilot study diagnostic instrument 117

4-3 Analysis of numerical response answers to question 8 in the pilot diagnostic instrument 120

4-4 Cross-tabulation analysis of student answers to questions 8-1 and 8-2 in the main study diagnostic instrument 125

4-5 Cross-tabulation analysis of student responses to two-tiered question 2 in the main study diagnostic instrument 134

4-6 Cross-tabulation analysis of student responses to two-tiered question 3 in the main study diagnostic instrument 136

4-7 Five-step method: A qualitative decision routine used to predict the products and spontaneity of reactions using the redox table 137

4-8 A student's calculation of cell potential on a worksheet assignment 138

4-9 Cross-tabulation analysis of student responses to two-tiered question 9 in the main study diagnostic instrument 150

4-10 Coding analysis for the theme of the interaction of science, technology and society (STS) in *Nelson Chemistry*, 1993 155

4-11 Coding analysis of level of inquiry in laboratory activities in the electrochemistry unit in *Nelson Chemistry*, 1993 161

4-12 Level of representation used by students for routine voltaic cells in the prediction, observation or explanation stage of the task-based interviews 164

4-13 Level of representation used by students for non-routine voltaic cells in the prediction, observation or explanation stage of the task-based interviews 164

4-14 Level of representation used by students for electrolytic cells in the prediction, observation or explanation stage of the task-based interviews 164

4-15 Amount of time given to electrochemical cell concepts during the 16 classroom observation periods 165

4-16 Electrochemistry alternative conceptions used to develop the distractors for questions in the main study diagnostic instrument 172

4-17 Cross-tabulation analysis of two-tiered question 5 in the main study diagnostic instrument 177

4-18 Cross-tabulation analysis of two-tiered question 6 in the main study diagnostic instrument 180

4-19 Cross-tabulation analysis of two-tiered question 7 in the main study diagnostic instrument 183

4-20 Cross-tabulation analysis of two-tiered question 10 in the main study diagnostic instrument 190

4-21 Cross-tabulation analysis of two-tiered question 4 in the main study diagnostic instrument 199

4-22 Cross-tabulation analysis of two-tiered question 1 in the main study diagnostic instrument 203

4-23 Alternative conceptions identified in this study 207

5-1 Alternative conceptions identified in this study that were previously unreported in the literature 225

D-1 Alternative conceptions for electric circuits and electric current concepts 289

D-2 Alternative conceptions for cell potential concepts 290

D-3 Alternative conceptions for oxidation and reduction concepts 290

D-4 Alternative conceptions for voltaic cells 291

D-5 Alternative conceptions for electrolytic cells 292

D-6 Alternative conceptions for electrical neutrality in electrochemical cells 294

LIST OF FIGURES

1-1 Types of knowledge discussed in this study 10

2-1 Problem-solving strategies 42

2-2 Three levels of representation of knowledge in chemistry 45

3-1 Two-tiered question 3 from the pilot study diagnostic instrument 63

3-2 Two-tiered question 4 in the pilot study diagnostic instrument 78

3-3 Two-tiered question 2 in the teacher version of the pilot study diagnostic instrument 80

3-4 Two-tiered question 5 in the pilot study diagnostic instrument 83

3-5 Two-tiered question 5 in the teacher version of the main study diagnostic instrument 86

3-6 Analytical hierarchy used to analyze data in the research study 106

4-1 Relationship among the three categories used for the framework of analysis in this study 108

4-2 Procedural knowledge question 7 in the pilot study diagnostic instrument followed by an open response question to obtain information about student problem-solving strategies 116

4-3 Procedural knowledge question 7 in the pilot study diagnostic instrument followed by an open response question to obtain information about student problem-solving strategies 119

4-4 Two-tiered questions 8 in the main study diagnostic instrument used to obtain information about student problem-solving strategies for stoichiometry problems 124

4-5 A representation of the copper-zinc voltaic cell using a porous cup that students assembled during the task-based interview 128

4-6 A representation of the copper-zinc voltaic cell using a salt bridge that students assembled during the task-based interview 128

4-7 A textbook diagram that illustrates the redox spontaneity rule and shows a pattern that can be memorized 131

4-8 Two-tiered question 2 in the main study diagnostic instrument 133

4-9 Two-tiered question 3 in the main study diagnostic instrument 135

4-10 A representation of a non-routine voltaic cell that students assembled during the task-based interview. This cell had two electrodes in one electrolyte and will not operate because no reduction reaction can occur; an oxidizing agent is not present. 141

4-11 A representation of an electrolytic cell design that students set up during the task-based interview that could be used to electroplate solid copper onto the inert cathode of the cell 145

4-12 A representation of the most common electrolytic cell that was set up by students during the task-based interview 146

4-13 Two-tiered question 9 in the main study diagnostic instrument 149

4-14 Two-tiered question 5 in the main study diagnostic instrument 176

4-15 Two-tiered question 6 in the main study diagnostic instrument 179

4-16 Two-tiered question 7 in the main study diagnostic instrument 182

4-17 A representation of the copper-zinc voltaic cell with a copper wire replacing the salt bridge that students assembled during the task-based interview 184

4-18 Two-tiered question 10 in the main study diagnostic instrument 189

4-19 A representation of the copper-zinc voltaic cell that students assembled during the task-based interview in which students replaced the zinc electrode with an inert carbon electrode. This design will not operate because it does not contain a reducing agent to supply electrons for the cell from an oxidation reaction. 192

4-20 Diagram identifying polarity of electrodes in a voltaic cell 196

4-21 Two-tiered question 4 in the main study diagnostic instrument 198

4-22 Two-tiered question 1 in the main study diagnostic instrument 202

5-1 The relationship between the novice-expert continuum and the category of problem solver, type of problem, and problem-solving strategy 215

5-2 Relationship among levels of representation of knowledge in chemistry showing increasing conceptual knowledge on the continuum from novice to expert 224

5-3 A voltaic cell diagram showing three levels of representation of knowledge in chemistry: symbolic, macroscopic, and particulate 232

5-4 A voltaic cell diagram showing the particulate level of representation of knowledge in chemistry 232

CHAPTER I

THE PROBLEM

Introduction

The nature of science and scientific inquiry has guided my approach to teaching science in high school. Typically, nature of science refers to the epistemology of science, science as a way of knowing, or the values and beliefs inherent to scientific knowledge and its development (Lederman, 1992). These characterizations are fairly general and philosophers, historians, and sociologists of science are quick to disagree on a specific definition of the nature of science (Abd-El-Khalick, Lederman, Bell, & Schwartz, 2001). The aspects that are accessible to students and relevant to their daily lives are that scientific knowledge is tentative, empirically-based, subjective (theory-laden), partly the product of human inference, imagination, and creativity, and socially and culturally embedded (Abd-El-Khalick et al., 2001). Scientific inquiry, or scientific processes, involves activities related to the collection and interpretation of data, and the derivation of conclusions (National Research Council, 1996), such as observing and hypothesizing. Related conceptions of the nature of science include the understanding that observations are constrained by our perceptual apparatus, that the generation of hypotheses necessarily involves imagination and creativity, and that both activities are inherently theory-laden. My emphasis on laboratory science activities and the use of student-designed experiments in my classrooms reflects the most enjoyable experiences of scientific inquiry in my own education. Through designing and conducting experiments as a scientist I have gained an understanding and appreciation for the process of science and the need for understanding the nature of science.

Beginning my Story

The story of how I came to teach science and my own relationship to the subject I teach and its curriculum, may bear resemblance to some teachers' stories, yet differ dramatically from those of others. Mine goes like this ….

My first introduction to scientific inquiry occurred in grade eleven when I was given the opportunity to design an experiment for a class project. I had observed that men who worked in forestry and agriculture, industries prevalent in the area where I lived, all appeared to be very healthy, especially by comparison to those who worked indoors. This observation lead me to hypothesize that men who worked outdoors must have a greater number of red blood cells in their blood because I assumed that there would be a higher concentration of oxygen in fresh outdoor air compared to the "stale" air breathed by those who worked indoors. My science teacher found a micrometer, some haemocytometers and a box of lancets in a dusty box in a storage room. I was allowed to take these and a microscope home with me and I proceeded to take over the family den for my laboratory. I pored over the instructions for counting blood cells with the haemocytometers and practiced taking blood samples from my reluctant siblings. When I was confident with my technique, I prepared my interview questions. Finally I was ready to collect data.

My family owned a service station in a small town and many people passed some time exchanging stories with my father at the front counter. To these men I explained my idea and asked for their participation in my study. Woodsmen, farmers, and businessmen alike agreed to allow me to interview them, collect a few drops of their blood and pursue the answer to my question. They were surprisingly supportive of the endeavours of a fledgling scientist.

After I had finished collecting my data, my teacher helped me complete some simple statistics, the results of which proved to be significant. I had indeed confirmed that men who worked outdoors had a much higher number of red blood cells in their blood. One of my father's customers was the town's physician and upon hearing the results of my study, he became very interested in my selection of participants. He asked questions about the general health of my subjects, which I realized had not been considered in my study. On his next visit, he kindly provided me with numerous medical books from the hospital library. I was intrigued to realize that my question was more complex than I had imagined and although I had data to support my hypothesis, the experiment had been conducted in far from the carefully controlled conditions that I was certain had been established.

Although the research project came to an end, my interest in research had just begun. This journey lead me through a Masters in Science, various projects in research and field laboratories, and finally to science classrooms. My hope for my students was that they too would come to appreciate the nature of science through

> participating in investigations that would provide a meaningful context to the curriculum.

Much has been written about what should be included as part of a science curriculum in order to promote a scientifically literate population (Bybee, 1997; Fensham, 2000; Hodson, 2001). In 1984, the Science Council of Canada published a report entitled *Science for Every Student: Educating Canadians for Tomorrow's World*. The report described the importance to Canada of having its citizens acquire a good working knowledge of science concepts and develop inquiry skills to apply these concepts to the world around them.

> Science education must be the basis for informed participation in a technological society, a part of a continuing process of education, a preparation for the world of work, and a means for students' personal development. (Science Council of Canada, 1984, p. 18)

In Alberta, the stated vision for science education is to provide students with a rich learning environment that will foster scientific understanding and life-long appreciation for the impact of science on their lives.

> Diverse learning experiences within the science program provide students with opportunities to explore, analyze and appreciate the interrelationships among science, technology, society and the environment and to develop understandings that will affect their personal lives, their careers and their futures (Alberta Education, 2007a) .

Both of these documents stress the importance of conceptual knowledge, or understanding, in science. However, there is a range of definitions for science, the interpretation of which leads to different educational goals. In the broadest sense, science refers to "the intellectual and practical activity encompassing the systematic study of the structure and behaviour of the physical and natural world through observation and experiment" (Canadian Oxford Dictionary, 2004). Science is also defined as "the arrangement of concepts in their rational connection to exhibit them as an organic, progressive whole" (Hegel, 1995). Here the term concept refers to a mental picture formed by combining the aspects of a class of objects. Based on my experience in scientific research, I believe that the study of science in high school should attempt to teach the systematic and verifiable process of science with the goal of understanding the connectivity of our experiences. This holistic goal of science involves inductive reasoning, which by its very nature, is more open-ended and exploratory. My grade 11 science project was inductive in nature because I was trying to infer a general law about factors affecting the composition of blood from particular instances provided by the subjects in my study. It also showed me the importance of holism because by looking at an isolated factor, I failed to account for the organic complexity of my subjects and was lead to a false, albeit verifiable, conclusion. My indoctrination into research science taught me that science is not merely the detached following of the steps in the scientific process but more so the seeking of patterns to come to an understanding of the complex system of which we are a part. This involves inductive reasoning as defined by Haverty, Koedinger, Klahr, and Alibali (2000): "the ability to detect and symbolically represent data patterns". Realistically, activities in the science classroom, however, may be more rationalist in that they seek to verify a specific concept rather than a holistic exploration of the phenomena under study. Activities for the verification of science concepts can be efficient in teaching factual knowledge and skill acquisition. Indeed parents and students desire such efficiency in education; however, science education should involve more than the rote following of rules and processes and foster a deeper understanding of the concepts and their connectivity.

In my science classroom the pedagogical perspective to which I adhere is that by doing science, students might come to understand and appreciate it. To that end my classrooms are active places where students move between empirical and theoretical tasks as I guide them through the procedural and conceptual knowledge needed to understand the topics being studied. Because my lessons focused on "doing" science by using student collected data as the basis for teaching concepts, it made sense to me to develop a way to assess student understanding in practical ways for summative assessment rather than the more traditional paper-and-pencil method. I felt that a demonstration of knowledge in novel problem-solving tasks would give me a better assessment of their understanding. To my surprise, I observed that some strong academic students were frustrated and thwarted when required to apply their knowledge in a novel situation while some students who were labeled weaker by more traditional assessment methods were able to excel. I began to question how it was possible that students who were very successful academically seemed to lack the understanding needed to apply their knowledge in new situations. I also began to question how the instructional methods that I used to implement the program of studies failed to promote understanding in science for some students.

Good curriculum, instruction and assessment should be focused on developing and deepening an understanding of important ideas and curriculum developers acknowledge a variety of types of knowledge (Carson, 2004; Young, 2003). In the domain of science, these can include content, conceptual, procedural, schematic, and conditional knowledge, in addition to practical reasoning and scientific investigation. From a constructivist perspective, it is important to understand how students use knowledge to construct a personal understanding of science.

Research in science education involves a complex interplay between the analytical perspective of the physical sciences and the more global perspective of the social sciences that encompasses a variety of learning theories from behaviorism to constructivism (Herron & Nurrenbern, 1999) to complexity and ecological discourses (Davis, 2004). Thus a chemical education researcher's working theory of learning shapes their approach to chemical education. This is unlike theories in science where ideas like the atomic molecular theory (the idea that elements are made up of unique atoms that in turn are comprised of subatomic particles, the movement of which theoretically explains the domain of electrochemistry) provide a mental framework that shapes all chemists' thoughts about chemical processes.

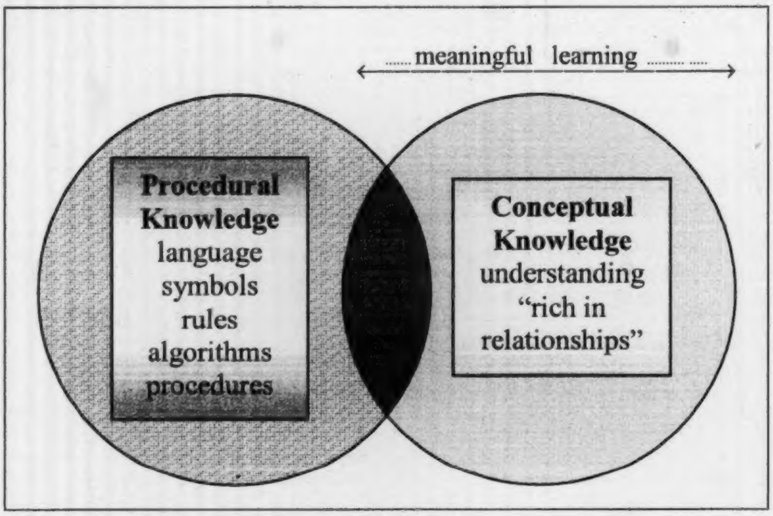
A strong implication from cognitive teaching and learning is that varieties of knowledge in science are not mutually exclusive (Glaser, 1984; Resnick, 1989). It may be that an educational program that attempts to separate the teaching and learning of content from the teaching and learning of scientific processes could prove to be ineffective in helping students to develop scientific reasoning skills and conceptual knowledge. School science stresses science-as-knowledge and typically divorces science-related issues from more meaningful contexts that could promote understanding. In Alberta, there are four program foundations for science: attitudes, knowledge, skills, and Science, Technology and Society (STS), all of which allude to meaningful contexts for education. For example, a knowledge foundation in the *Chemistry 20-30 Program of Studies* states that, "*Students will* construct knowledge and understandings of concepts in life science, physical science and Earth and space science, and apply these understandings to interpret, integrate and extend their knowledge" (Alberta Education, 2007a). In the classroom; however, teachers may focus on the specific knowledge outcomes such as "define oxidation and reduction operationally and theoretically" because these are the testable items on the external, standardized test. Some "teaching to the test" is inevitable, given the pressures associated with external evaluation, but it becomes a question of degree. Teachers are induced to teach to the test with the result that the curriculum is becoming increasingly test-driven. As Meaghan and Casas (1995) reported, many teachers "align their curriculum with what will be tested, are concerned that standardized testing narrows the curriculum by focusing on information that is testable in a paper-and-pencil format and feel pressure to improve on test scores" (p. 47). Wideen, O'Shea, Pye, and Ivany (1997) used comparative case studies of two school districts to examine the impact of the grade 12 school-leaving examinations on the teaching of science in British Columbia. They concluded that the high-stakes tests reduced the variety of instructional approaches used because they "discouraged teachers from using strategies which promoted inquiry and active student learning", and that "this impoverishment affected the language of classroom discourse"

(p. 428). Popham (2000) asserted that faced with increasing pressure from politicians, school district personnel, administrators, and the public, some teachers have begun to employ test preparation practices that are clearly not in the best interest of children. These activities included relentless drilling on test content, eliminating important curricular content not covered by the test, and providing interminably long practice sessions that incorporate actual items from these high-stakes standardized tests. In US schools, the increasing emphasis on the use of "test-oriented accountability measures" (Darling-Hammond, 1991, p. 222) parallels a decline in teaching methods such as essay writing, research projects, laboratory work, and student-centred discussions designed to foster higher-order learning skills (Crick, Jones, & Jones, 2003; Darling-Hammond, 1991; Thomas, 2005). This emphasizes our departure from the Science Program Vision, "to develop in students the science-related knowledge, skills and attitudes that they need to solve problems and make decisions and, at the same time, to help students become lifelong learners who maintain their sense of wonder about the world around them" (Alberta Education, 2007a). In order to make good decisions about science related issues, it is important for students to develop both procedural knowledge and conceptual knowledge in science (see Figure 1-1).

In educational literature, there is little agreement on definitions related to types of knowledge. In literature related to research in science and mathematics education, the term procedural knowledge is associated with lower-level knowledge including rote and algorithmic learning (e.g., Bowen & Bunce, 1997; Hiebert & Lefevre, 1986; Smith, 2002). In the cognitive psychology literature, procedural knowledge is associated with higher-level knowledge involving more substantive thinking (e.g., Gott, Duggan, & Johnson, 1999; Mayer, 2008). In this paper, the definitions of procedural and conceptual knowledge from the mathematics and science education literature will be used (see Figure 1-1).

In this study, a procedural knowledge question could involve the calculation of mass changes at the electrodes in electrochemical cells using a mathematical formula. However, conceptual knowledge is required to understand that it is the difference in electrical potential between the two electrodes and the resulting electron movement that produces the mass changes in the redox reaction.

Figure 1-1. Types of knowledge discussed in this study. In the diagram, meaningful learning is represented by conceptual knowledge and the overlapping area between the two types of knowledge.


meaningful learning
Procedural Knowledge
language
symbols
rules
algorithms
procedures
Conceptual Knowledge
understanding
"rich in relationships"

Study Overview

In this study, I discuss knowledge in science, representations of knowledge in chemistry, conceptions and alternative conceptions in electrochemistry, and constructivist theories of learning popular in science education. I chose to focus on the field of electrochemistry for this research for several reasons. Electrochemistry has been identified as one of the most difficult topics in chemistry (Bojczuk, 1982; Butts & Smith, 1987; de Jong, Acampo, & Verdonk, 1982 (as cited in de Jong, Acampo, & Verdonk, 1995); Finley, Stewart, & Yarroch, 1982; Sanger & Greenbowe, 1997), and there is a rich body of literature that has identified alternative conceptions that students hold in this field (de Jong, 1995; Garnett & Treagust, 1992a; 1992b; Sanger & Greenbowe, 1997a; 1997b; Ogude and Bradley, 1994; 1996; Ozkaya, 2002). Students in Alberta are introduced to electrochemistry in grade 9 but do not address the topic again until grade 12, unlike curricula in other countries where it is covered in two or more successive grade levels (e.g., the United Kingdom: Bojczuk (1982); the United States: Finley et al. (1982), Sanger & Greenbowe (1997a; 1997b); Australia: Butts & Smith (1987); and the Netherlands: de Jong (1982)).

Research has found that students tend to ignore instruction that does not coexist well with their existing or prior knowledge, or they will reinterpret the information to match their expectations (Driver & Easley, 1978; Wandersee, Mintzes, & Novak, 1994) from previous exposure to the information. The research into alternative conceptions and specifically alternative conceptions in electrochemistry will be reviewed and its implications in the classroom will be examined. A diagnostic instrument to identify alternative conceptions was developed for this study. The early diagnosis of alternative conceptions, immediately following the teaching of the related concepts, may allow teachers to provide students with opposing information and experiences that would contradict their alternative conceptions, a cognitive conflict that has been recognized in facilitating conceptual change in students' understanding (Vygotsky, 1978). Similarly, according to Mischel (1971), the "cognitive conflicts which the child himself engenders in trying to cope with his world, are then what motivates his cognitive development; they are his motives for reconstructing his system of cognitive schemas…" (p. 332).

Statement of Purpose and Research Question

The purpose of this research was to explore student learning in electrochemistry and attempted to answer the question,

At the end of a unit of study, what are students' understandings of electrochemistry?

The following three categories comprised the framework of analysis for the study.

I. Types of knowledge used in problem solving
II. Levels of representation of knowledge in chemistry
III. Alternative conceptions

Significance of the Research

Each of the individual categories used in the framework of analysis have been previously reported in the literature. For example, Gabel and Bunce (1994) provided an extensive review of the early literature on problem solving in chemistry. More recently, research has been reported on the type of knowledge used to solve problems (e.g., Williams, Ma, Prejean, Ford, & Lai, 2008) and problem solving strategies (e.g., Meltzer, 2007; Reid &

Yang, 2002; Selvaratnam & Canagaratna, 2008). A number of authors have explored students' interpretations and use of the levels of representation of knowledge in chemistry and the impact on their understanding. These studies have been conducted with students in high school (e.g., Furió-Más, Calatayud, & Bárcenas, 2007; Wu, 2003) and undergraduate (e.g., Chittleborough & Treagust, 2008; Nicoll, 2003) chemistry classes and with high school chemistry teachers (Kruse & Roehrig, 2005). Strategies to improve students' understanding of the particulate level of representation of knowledge in chemistry have also been explored (e.g., Han & Roth, 2006; Sanger, Campbell, Felker, & Spencer, 2007; Yezierski & Birk, 2006). A rich literature on alternative conceptions in chemistry exists and recent research reports on their influence on learning (e.g., Hamza & Wickman, 2008; Kruse & Roehrig, 2005; Leman & Burçin, 2007; Yezierski & Birk, 2006). A number of recent studies have addressed two of the three factors used in this study. For example, problem solving and the particulate level of representation have been examined (e.g., Barak & Dori, 2005; Sanger, Brincks, Phelps, Pak, & Lyovkin, 2001; Sanger, Campbell, Felker, & Spencer, 2007; Williamson, Huffman, & Peck, 2004), in addition to alternative conceptions and the particulate level of representation (Nicoll, 2003). Previous research has also explored how teachers use the constructivist framework in teaching electrochemistry (e.g., Acar & Tarhan, 2007; Sanger & Greenbowe, 2000).

This research contributes a comprehensive, descriptive study on the influence of all three factors on student understanding. Concentrating on one factor may result in a deeper understanding of its influence on student learning, but this method may not reflect the complexity of students' understandings in a field of study. In order to give students and teachers insight about, and understanding of, this complexity it seemed appropriate to focus this study on all three factors when exploring student understandings at the end of a unit in electrochemistry. The findings may contribute further to our understanding of students' conceptions of electrochemistry. Furthermore, understanding the influence of the three factors on how students make sense of this field may result in a better understanding of classroom practice that could promote the acquisition of conceptual knowledge – knowledge that is "rich in relationships".

Definition of Terms

In this section, several key terms used for the study are defined.

Alternative conception – knowledge that is inconsistent with, or different from, scientific consensus (Wandersee, Mintzes, & Novak, 1994)

Cognitive structure – the set of concepts that are linked with the students' other concepts to form an integrated conceptual framework of chemical knowledge (West, Fensham, & Garrard, 1985)

Concept – a perceived regularity in events or objects, their records, designated by a label. The label for most concepts is a word or group of words (Novak & Cañas, 2008)

Conceptual knowledge – the ability to perceive the significance, explanation or cause, or have mastery of a subject, skill, etc. (Hiebert & Lefevre, 1986) (e.g., understanding the relationship between the concepts of electrical potential, electrodes, electron movement, and spontaneous redox reactions when predicting observations for an electrochemical cell). It is also known as relational understanding (Skemp, 1978), deep learning (Chi, Bassok, Lewis, Reiman, & Glaser, 1989), or real learning (Holt, 1964)

Decision routine – a specific framework or procedure used to organize information around a theme (Sweller, 2006)

Electrochemical cell – a system in which two electrodes are in contact with an electrolyte; the two types include electrolytic cells which require energy and voltaic cells which produce energy (Oxford Dictionary of Chemistry, 1996)

Electrolytic cell – an electrochemical cell in which a current from an outside source is passed through the electrolyte to produce a chemical change (Oxford Dictionary of Chemistry, 1996)

Learning – a process that is permanent and experience-based and can result in understanding. Rote learning results in non-understanding with good retention but poor transfer performance; whereas, meaningfull learning results in understanding with good retention and good transfer performance (Mayer, 2008)

Levels of representation of knowledge in chemistry – includes macroscopic, particulate and symbolic levels (Johnstone, 1991)

Macroscopic representation – involves observation and tactile manipulations in science (e.g., setting up an electrochemical cell in the laboratory and recording observations as it operates) (Johnstone, 1991)

Particulate representation – involves microscopic, molecular, atomic, and subatomic entities (Johnstone, 1991) (e.g., the movement of electrons in an electrochemical cell)

Procedural knowledge – the grasp of the formal language (symbol representations) and rules, algorithms or procedures (Hiebert & Lefevre, 1986); Also known as apparent learning (Holt, 1964), instrumental understanding (Skemp, 1978), or algorithmic learning (Bodner, 1986)

Symbolic representation – involves the use of chemical formulas and mathematical manipulation (e.g., calculating the change in mass of an electrode in an electrochemical cell by using a mathematical formula; writing a chemical equation) (Johnstone, 1991)

Two-tiered questions – the first tier of each question assesses procedural knowledge; the second tier assesses conceptual knowledge and is based on a reason for the choice in the first tier (Peterson & Treagust, 1989; Treagust, 1988)

Voltaic cell – an electrochemical cell in which a spontaneous reaction between the electrodes and electrolyte(s) produce a potential difference between the two electrodes and results in the generation of electrical energy (Oxford Dictionary of Chemistry, 1996)

Research Ethics

Ethical approval was granted for both the pilot study and the main research study from the University of Alberta Research Ethics Board. Written consent was obtained from all students (and parents of students under 18 years old), and teachers for audio recording interviews and the collection of student and teacher artifacts. The students were made aware that their participation was voluntary and that they could opt out at any time by either informing the teacher or the researcher. To ensure anonymity, pseudonyms are used for the students and teachers in this study.

Interpretation and Representation

In describing students' experiences, great effort was made to use the students' own words as much as possible. Interpretations and explanations were derived from an understanding of constructivist ideas. There were questions and issues that I had to reflect upon in the writing of this dissertation, such as Who is doing the talking? Who am I talking about? Do I really know the students' experiences? How do I represent the richness or perspectives of their experiences, reflections, and constructions? What criteria do I use to select what to represent as experience? In her chapter on *Writing Up and Reporting Mixed Methods Social Inquiry,* Greene (2007) distinguishes between the requirements of quantitative and qualitative researchers and readers. The different aspects of the two paradigmatic traditions must be treated equitably and respectfully to signal "legitimation of multiple ways of knowing and acceptance of diverse experiences, perspectives, and understandings" (pp. 181-182). I have tried to keep the traditions of the two interpretive communities visible so that the reader and I do not forget that I am the one writing and in writing I bring forth myself, and my understanding of myself and my world.

Delimitations of the Study

My research inquiry is delimited to how students in two urban high schools understand electrochemistry. It will not include analysis of the teachers' knowledge or understanding in the seven classrooms involved in the study. Further, it will not attempt to develop teaching strategies to address the identified alternative conceptions or their sources. The ability of the diagnostic instrument to identify alternative conceptions and the relationship of procedural and conceptual knowledge will be addressed on a small scale, but the large-scale test of validity of this instrument is not a focus of this research. Rather, I consider this study a beginning step on my journey of inquiry – a building block in a future program of research.

The following considerations will constrain the domain of my research in this study.

1. While I recognize that the classroom learning environment is a complex social system, I will focus my attention on the interaction of students with the material being studied during classroom observation sessions to provide a common vocabulary for my discussions with students and to familiarize myself with their laboratory procedures.
2. Since my unit of analysis is the knowledge and its representation by individuals, there will be no attempt to describe the actions or interactions of class members during observations in the classes participating in the study.
3. My study focuses on activities involving electrochemical cells. A rich body of literature on alternative conceptions in this field exists and students may incorporate information from previous science and chemistry classes.
4. The teacher's interpretations of students' knowledge and understanding will not be a direct focus of my attention. It is recognized that the shared and personal histories of the teacher and students in a classroom are an important influence on what I observe and the nature of my engagement with students. The teachers whose classrooms are participating in the study participated in a group interview to attempt to make sense of the research findings through the knowledge of their shared experience with their students.
5. The setting selected for the study was two urban high schools involving all the teachers assigned to Chemistry 30 so demographic differences should have a minimal impact on the results of the study.

6. Since the purpose of this study is to explore students' understandings of electrochemistry, teaching practices will not be a focus and will not be analyzed or critiqued. However, it was important for me to become familiar with how students' experienced the information during this unit. Classroom observations and the examination of teaching and learning artifacts and resources were used to help me become familiar with the language and practices used during the unit and to provide a context during interviews and during the analysis of the diagnostic instrument.

Limitations of the Study

I recognize the inherent limitations imposed by my data gathering methods – namely

1. verbal discourse with its multiple meanings and interpretations
2. observation, as incorporating a frame of reference of the observers
3. written work and verbal instruction produced in a context of which I am not a part
4. the ability of the students to communicate their knowledge about abstract ideas
5. if a student confronts an alternative conception during the task-based interview process, then it may not be identified or validated by triangulation during the diagnostic instrument interview
6. the legitimacy of considering self-explanations as a source of verbal protocols because the process of generating self-explanations may alter the processing of the to-be-learned materials
7. the legitimacy of the researcher's role as a participant observer during the classroom observations and the interviews because the process of interacting with

students may alter what they pay attention to and the way that they learn the material (this is elaborated in Chapter III)

8. the use of a limited number of schools and classes, and a small number of students limits the generalizability of the findings
9. issues of validity (whether I am measuring what I intend to measure or with how the observations are influenced by the circumstances in which they are made) because of the use of mixed methods in the research

Assumptions

According to Siegler (1995), learning occurs when students are provided with feedback and are asked to explain their reasoning. In this study, it must be assumed that learning can occur because of the use of a task-based interview protocol (Goldin, 2000) and a predict-observe-explain (POE) task framework (White & Gunstone, 1992). During the task-based interview, students could make predictions that may be verified or not by their observations. This may influence their explanations related to the operation of electrochemical cells. This could impact the identification of alternative conceptions during the interviews related to the diagnostic instrument as students may have already identified and confronted a discrepancy in their learning as a result of the interview process. To accommodate this, student answers on the diagnostic instrument, both correct and incorrect, were recorded and then removed prior to the interview so that discrepancies could be determined.

It is also assumed that how students use language represents their thinking about what they are learning and that this will allow me to come to an understanding about how they have inter-related the various types of knowledge in their cognitive framework in electrochemistry.

Summary of the Forthcoming Chapters

In this section, the content of the upcoming chapters will be summarized.

The literature review chapter, Chapter II, reviews the research carried out on learning in science, emphasizing the constructivist perspective. The three categories that comprise the framework of analysis for the study are explored. Two types of knowledge, procedural and conceptual, are discussed and their influence on problem-solving in chemistry is examined. The relationship among the three levels of representation of knowledge in chemistry is explored. The research on alternative conceptions in chemistry is presented and methods to identify them are discussed.

The methodology chapter, Chapter III, describes how the research was planned and designed. It outlines the research procedures applied, and how the research instrument was planned and developed, including the pilot study. Changes to the main study diagnostic instrument and the interview protocol resulting from the pilot study are identified and discussed. The data collection and analysis issues are explored as well. Moreover, it describes how the interviews were conducted and how the results were analyzed. Finally, limitations of the data collection are addressed.

Chapter IV presents the data obtained in both the pilot study and the main research study. The students' use of procedural and conceptual knowledge and the levels of representation of knowledge in chemistry are related to their ability to solve routine and novel problems. The students' alternative conceptions, including fifteen that were previously unreported, are identified and some possible sources are discussed. The chapter also summarizes the results of the diagnostic instrument for alternative conceptions and discusses its usefulness as an instructional tool.

The final chapter, Chapter V, summarizes how the three categories in the framework of analysis are inter-related and how this may limit students' ability to understand electrochemistry. Finally, the implications for the teaching of electrochemistry are reviewed.

CHAPTER II

REVIEW OF RELATED LITERATURE

Introduction

> Knowledge is not a copy of reality. To know an object, to know an event, is not simply to look at it. To know an object is to act on it. To know is to modify, to transform the object, to understand the process of its transformation, and as consequence to understand the way the object is constructed. (Piaget, 1964, p. 176)

Ever since the classical studies of Piaget, there has been interest in the conceptions of physical science held by young children (Osborne & Wittrock, 1983). Even a casual observer of the field of science education over the last two decades is familiar with the unprecedented exposure of the ideas held by children, adolescents, and to a lesser extent by adults, about a wide range of scientific phenomena (e.g., Li & Li, 2008; Olsen, 2008; Smith & Abell, 2008). Several thousand research studies have been published including over one hundred revealing students' ideas in chemistry. These data, compiled by Duit (2007), have now reached over 7700 entries. Research in this domain has attempted to answer questions relating to how conceptions and alternative conceptions occur, their origin, how extensive they are, and of course how teachers can address them (Gil-Perez & Carrascosa, 1990).

It is understandable why students' ideas concerning chemical phenomena have become a focus of research. Students from all levels, from elementary to post-secondary, struggle to learn and understand chemistry and many remain unsuccessful (Nakhleh, 1992).

Research shows that many students do not understand fundamental concepts and many conceptions that are understood differently from scientific canon go unchanged from the early years of schooling, through university, and even to adulthood (Gil-Perez & Carrascosa, 1990). By understanding fundamental concepts differently, many students have trouble with more advanced concepts that build upon these fundamental ones (Thomas, 1997).

Research Project Overview

My study was comprised of mixed methods research involving both qualitative and quantitative techniques. It involved two phases that were conducted in urban high schools in Alberta, Canada. The pilot study was conducted in one high school with 23 students and their teacher in two Chemistry 30 classes. The main study involved 4 teachers and 87 students at two urban high schools. Since the purpose of this study was to explore students' understandings of electrochemistry, teaching and learning were observed in order to become familiar with the language, assignments and activities in which the students were engaged during the unit. Semi-structured, task-based interviews were conducted while students were setting up and operating two types of electrochemical cells in the laboratory. A two-tiered, multiple-choice diagnostic instrument was developed to identify alternative conceptions that students held at the end of this unit and to identify the type of knowledge that students used when solving electrochemical problems. The framework of analysis that was used was comprised of three categories: types of knowledge used in problem solving, levels of representation of knowledge in chemistry, and alternative conceptions. Teachers participating in the study explored the research findings and discussed their impact on teaching and learning.

Theoretical Background

Constructivist Paradigm

An important issue in science education is the understanding of how learners construct knowledge. In the last three decades, the perspectives of constructivism on learning and teaching have been strongly advocated by science educators and researchers (Wu & Tsai, 2005). Constructivism is a theory about "knowing" and "learning" (Bodner, 1986), asserting that knowledge cannot be directly transmitted but must be actively constructed by learners. This view of learning also highlights the significance of the individual learner's prior knowledge in subsequent learning (Ausubel, 1968; 2000). The learner's constructs represent the view that they have constructed about the world as they experienced it, and their constructs guide how they are likely to construe the world as they continue to experience it. Their construct system is their history and their predisposition to perceive (Kelly, 1955).

From a sociocultural perspective this is seen as essential for tackling the complexities of contemporary life. According to Simon (1996), the ever increasing growth of easily accessible information has shifted the meaning of "knowing" from being able to remember and repeat information to being able to find and use it effectively and efficiently. Developments in cognitive science do not deny that facts are important for thinking and problem solving, but show clearly that "usable knowledge" is not the same as lists of decontextualized facts. Being able to use knowledge to solve new types of problems requires the understanding of that knowledge. Thus, suggestions for new teaching and learning practices emphasize learning with understanding (Bransford, Brown, & Cocking, 1999; Perkins, 1993). Such learning is closely related to thinking and reasoning as represented by Perkins and Unger (1999), "Understanding a topic is a matter of being able to think and act creatively and competently with what one knows about the topic ... The ability to perform in a flexible, thought-demanding way is a constant requirement" (p. 97).

The literature on the constructivist view of learning has revealed that learning is a much more complex operation than simply transferring knowledge from the instructor's brain to the students', and "piling it up" in their memory (Osborne & Wittrock, 1985), which is the hallmark of traditional teaching methods, such as lectures and demonstrations. It is an individual, cognitive activity that involves social participation and practice in order for the student to become acquainted with the culture and the "way of seeing" of the science community (O'Loughlin, 1992; Scott, Asoko, & Driver, 1991). Learning is seen as an ongoing, recursive activity based on the learners' interpretation of their interactions with the world, which may lead to understanding. Knowledge obtained from this interaction is largely not conscious. It is emergent in that it is continuously modified as we gather information using interpersonal dynamics and cultural tools, the most important of which is language. Thus learning requires individual cognitive engagement (personal constructivism) as well as social practice (social constructivism) (Duit & Treagust, 1998). Both personal and social constructivism locate knowledge within individual learners; however, they differ in the details of how it developed (Geelan, 1997).

Personal Constructivism

Personal constructivism involves a perspective on the nature of knowledge and a view of the nature of the learner. Learners are viewed as persons who are actively involved in creating their own personal knowledge, which has individual meaning, from information to which they are exposed. Knowledge is thus considered to exist within a person. This idea is in accord with the fundamental views of epistemology expressed by Driver (1986), Kelly (1955), Piaget (1972), Pines and West (1988), and Wittrock (1974). Learning, therefore, is a purposeful activity on the part of the learner and requires active engagement which corresponds to Paulo Freire's (1970) concept of "intentionality", which he interpreted to be the act of being more fully human when engaged in inquiry and creative transformation. Individuals' existing conceptions influence the meanings that they construct in a given situation (whether a lecture, demonstration or laboratory activity), and what is learned results from an interaction between the learner's present conceptions or constructs and the various linguistic and sensory experiences provided.

From a constructivist perspective, the goal of the science teacher is to engage learners with phenomena in such a way that they will reveal their existing knowledge, both accurate scientific knowledge and alternative conceptions. Students actively select and order information (Driver, 1986), construct tentative models which may be seen as alternatives to more established views, and evaluate these views against personal criteria (Kelly, 1955; Pope & Gilbert, 1985; Wittrock, 1974). Students process knowledge like scientists do, by observing, interpreting, predicting, and evaluating so that more refined concepts evolve (Kelly, 1955; Koslowski, 1996; Kuhn, 1970). Concept development is seen as an evolutionary process which involves the progressive differentiation of cognitive structures. Existing memories and information-processing strategies of the brain influence the selection of stimuli and the meaning that comes to be associated with it (Wittrock, 1974). Consequently, prior knowledge, both everyday and school science knowledge, plays an important role in learning because it provides the foundation for subsequent learning and is used in the construction of new information.

The purpose of the student-teacher engagement is to act as a conduit for information about what the student knows, to be passed from the student to the teacher. Learning is conceptualized as a change of ideas by testing them against new experience. This shifts attention from what the teacher or program does to what goes on inside the learner (Dana & Davis, 1993):

> Students are sense makers. They interpret what has been said or read in light of what they already know; constructing knowledge … that fits their understanding of the world. The challenge for teachers, especially university teachers, becomes the question of how to design learning opportunities that result in maximal learning. (p. 328)

Designing teaching schemes to support science learning is therefore inherently problematic in that it requires some appreciation of the prior knowledge that students are likely to bring with them to the learning situation, while recognizing that individual learners make sense of learning experiences in personal ways. It is not possible therefore to design learning sequences in such a way that learning outcomes can be fully anticipated (Scott & Driver, 1998) so reflective practice, in addition to the collection of the evidence of learning, becomes a key component of effective teaching practices.

Social Constructivism

Many studies in science education have tended toward a social constructivist interpretation (Atherton, 2005; Beck & Kosnick, 2006; Larochelle, Bednarz, & Garrison, 1998; O'Loughlin, 1992). Implicit in this research approach is the notion of a correct scientific interpretation against which student responses are assessed. What is considered a correct scientific interpretation would be referred to as a component of a scientific paradigm (Kuhn, 1970) or an adequate conduct (Valera, Thompson, & Rosch, 1991), both of which imply the social construction and acceptance of scientific knowledge.

Science as a form of public knowledge is socially constructed and conjectural, in that opinions are formed on the basis of incomplete knowledge. It has become widely accepted that children develop ideas and beliefs about the natural world long before they are formally taught, and the importance of these conceptions for learning has been recognized by many researchers (e.g., Driver & Erickson, 1983; Driver, Guesme, & Tiberghein, 1985). In their position paper on a constructivist view of learning, Driver and Oldham (1986) state that

> [S]cience as public knowledge is not so much a discovery as a carefully checked construction … It follows that science in secondary schools involves not just knowledge about events and phenomena in the natural world, but an appreciation of theories as imaginative human constructions. (pp. 109-110)

Social constructivism emphasizes the importance of culture and context in understanding what occurs in society and constructing knowledge based on this understanding (McMahon, 1997) so that learning is viewed as a social process. It does not take place only within an individual, nor is it a passive development of behaviors that are shaped by external forces (McMahon, 1997). Meaningful learning occurs when individuals are engaged in social activities whether in a laboratory setting, classroom discussion, family interaction, or non-traditional education setting, such as a museum. These influences contribute to the knowledge that the student constructs while engaged in school science and they can lead to the development of conceptions at odds to those of canonical science.

Constructivist Perspective and Learning

Students build sensible and coherent understandings of the events and phenomena in their world from their own point of view (Osborne & Wittrock, 1983). With these coherent understandings in place, words such as "electron" and "redox" represent labels that stand for elaborated cognitive structures stored in the brain (West et al., 1985). These elaborated cognitive structures are themselves composed of interrelated concepts that are used to infer meaning for a particular topic. These concepts are then linked with the students' other concepts to form integrated cognitive structures of chemical knowledge. Learners selectively attend to the flow of information in the classroom, and their prior knowledge, both from their everyday experiences and school science, determine the information to which they pay attention. They then interpret this selected information and draw inferences based on stored information from past experiences. Students' newly generated meanings are then actively linked to their prior knowledge.

The constructivist research perspective has been useful in making science educators aware of the range of alternative ideas that students have about a variety of topics in science. Knowing about the range of ideas that can exist in a classroom is one thing; how to motivate a student to adopt a view that is consistent with the scientific position of canonical science is something else. The influence of motivation on conceptual change in learners' is an emerging field in educational research (Vosniadou, 2007). This warm (Mason, Gava, & Boldrin, 2008; Sinatra, 2005) or hot (Pintrich, Marx, & Boyle, 1993) conceptual change goes further than considering only cognitive factors on knowledge revision (Mason et al., 2008). Even when conceptions are apparently changed in an educational setting, earlier conceptions can quickly reassert themselves in the contexts of further schooling or the everyday world. The use of constructivist techniques relies on student verbalization of their ideas that are then interpreted by the teacher. It is assumed that how students use language represents their thinking about what they are learning. Unfortunately, it is possible that everyday meanings for scientific phenomena may promote resistant alternative conceptions. This may be particularly important if ideas in school science differ from culturally accepted views from the student's daily life. For example, the concept that opposites attract is accurate scientifically in the study of magnetism, is a socially accepted idea in relationships, but is opposite to the movement of charged particles in electrochemical cells. This has implications for how teachers try to make science relevant in the classroom.

As a human construction, scientific knowledge aims to represent a shared physical world. An important consequence of this position is that teaching schemes in science must have learning goals that are both conceptual and epistemological. The conceptual learning goals help students to understand and be able to use scientific frameworks in specific topic domains. The epistemological learning goals help students to recognize that scientific knowledge is conjectural and to gain an appreciation of the rational criteria, such as consistency and coherence, which are used by the scientific community in generating and validating knowledge claims (Scott & Driver, 1998). For example, a conceptual learning goal may be for students to be able to predict the spontaneity of electrochemical reactions by comparing the position of the reacting chemicals on a table of reduction half-reactions (redox table). The series of chemicals on this table (see Table 2-1) are arranged in order of their electrode potentials relative to the hydrogen electrode, represented by the hydrogen half-reaction $2\ H^{+}_{(aq)} + 2\ e^{-} \rightarrow H_{2(g)}$. Chemical species with a greater tendency to attract electrons are listed above hydrogen and those with a lesser tendency to attract electrons are listed below.

Table 2-1. An excerpt from the *Chemistry 30 Data Booklet* table of standard electrode potentials, also known as the redox table

Reduction Half-Reaction	Electrical Potential E° (V)
$AgBr(s) + e^- \rightarrow Ag(s) + Br^-(aq)$	+ 0.07
$2\ H^+(aq) + 2\ e^- \rightarrow H_2(g)$	0.00
$Pb^{2+}(aq) + 2\ e^- \rightarrow Pb(s)$	– 0.13
$Sn^{2+}(aq) + 2\ e^- \rightarrow Sn(s)$	– 0.14
$AgI(s) + e^- \rightarrow Ag(s) + I^-(aq)$	– 0.15
$Ni^{2+}(aq) + 2\ e^- \rightarrow Ni(s)$	– 0.26
$Co^{2+}(aq) + 2\ e^- \rightarrow Co(s)$	– 0.28
$PbSO_4(s) + 2\ e^- \rightarrow Pb(s) + SO_4^{2-}(aq)$	– 0.36

From: Alberta Education (2008a).

This information can then be applied to the study of chemical properties and reactions involving ions in solution, including electrolytic (electricity consuming) and voltaic (electricity producing) electrochemical cells. As an epistemological learning goal, students may come to appreciate that the development of such a table is dependent on the accuracy of the scientific instruments available, the procedural knowledge and skill of the scientists employing those instruments, and the values of the scientific community in which it was constructed.

A major change in social values contributing to attitudes about learning and knowledge in science has to do with significant reformation of what it means to be a successful science student. Performance assessment is increasingly accepted for tasks beyond laboratory and generic inquiry skills, and cognitive science research has demonstrated that higher-level thinking or reasoning is domain specific (Glaser, 1984). The demonstration of knowledge may be a more valid measure of learning than traditional methods of assessment which rely solely on language. For example, a practical demonstration of a working electrochemical cell using non-routine materials requires an understanding of the underlying theoretical concepts in order to make an appropriate selection of apparatus and to assemble a functional cell. Such an assignment requires conceptual knowledge and students relying on rote learning, which is more characteristic of procedural knowledge, may demonstrate limited success with this type of problem. Gobet (2005) suggested that the ability of experts to rapidly solve problems results from their use of perceptual cues developed from in-depth, domain-specific knowledge and the understanding of the connectivity of that knowledge. Decision routines, or schemas, which may appear procedural in nature, increase the rate of problem solving by unburdening the cognitive capacity of the decision maker (Bröder & Schiffer, 2006). But with experts, these are developed as a result of the understanding of the connectivity within the domain. Students who rely on rote learning lack this connectivity.

Procedural knowledge, therefore, can be attained either with rote learning, or in the context of meaningful learning. Koslowski, Susman, and Serling (1991), in a study of scientific reasoning in children, found that procedural knowledge of what a scientific experiment entails did not ensure competence in designing experiments because of a lack of understanding of experimental design. The careful design of assessment tasks was necessary to differentiate between procedural and conceptual knowledge and uncover student knowledge of the connectivity among chemical concepts. A lack of connectivity was apparent in the holistic question on a recent Alberta Chemistry 30 diploma examination. Students were asked to evaluate three methods of producing hydrogen gas given the chemical reactions, to choose a best method, and to justify their choice (Alberta

Education, 2006b). The majority of students were able to correctly complete the mathematical calculations to determine the energy change during the three reactions but lacked the conceptual knowledge of the energy processes that was necessary to recognize that the best method would consume the least energy. Instead, they misinterpreted the data and chose what they considered to be the reaction that produced the most energy, thus indicating that they did not know the meanings of the calculations, or the practical application of technology (Alberta Education, 2006a). Interestingly, teachers believed that the successful completion of the mathematics required in the problem should have been sufficient for a passing grade regardless of the clear indication of the lack of understanding in chemistry (Alberta Education, 2006a). This is consistent with the finding of de Jong et al. (1995) that although teachers may think that they are teaching for understanding (conceptual knowledge), their methods reinforce the value of rote learning, an efficient method for teaching procedural knowledge.

Framework of Analysis Categories

Category I. Types of Knowledge Used in Problem Solving

Procedural Knowledge

Hiebert and Lefevre (1986) used the term *procedural knowledge* to denote the grasp of the formal language (symbol representations), rules, algorithms, or processes in mathematics. Procedural knowledge is variously known as apparent learning (Holt, 1964), instrumental understanding (Skemp, 1978), factual knowledge (Mayer, 2008) or algorithmic learning (Bodner, 1986). Both Meltzer (2007), and Anderson and Krathwohl (2000) further differentiate factual and procedural knowledge. Factual knowledge is essentially seen as facts and terminology specific to a domain and procedural knowledge is denoted as the knowledge required to do something specific to a discipline such as methods, skills or algorithms. Procedural knowledge can reflect a rote-learning or superficial strategy where the learner knows a rule and is able to apply it. In spite of conceptual difficulties, many students are still able to solve quantitative problems in science correctly (e.g., Gabel, Sherwood, & Enochs, 1984; Stewart, 1985). This is done by relying on algorithms to arrive at correct answers, especially for basic or routine problems (Gabel & Bunce, 1994; Reid & Yang, 2002; Sloyer, 2003). The use of algorithms is not, as might be expected, limited to less able problem solvers. Reasons put forward to account for the dependence on algorithms for quantitative problem solving are that teachers and general chemistry courses frequently emphasize the application of algorithms to solve routine problems (Nurrenbern & Pickering, 1987), and that problems in textbooks include procedures which can be used algorithmically (Bodner, 1987).

Conceptual Knowledge

Conceptual knowledge is also known as relational understanding (Skemp, 1978), concepts knowledge (Mayer, 2008), deep learning (Chi, Bassok, Lewis, Reiman, & Glaser, 1989), or real learning (Holt, 1964), and is achieved by the construction of relationships among pieces of information. Either two pieces of information already stored in memory are linked, or a newly learned piece of information becomes linked with prior knowledge. Hiebert and Lefevre (1986) used the term *conceptual knowledge* to describe knowledge that is "rich in relationships" (p. 3) and they asserted that it cannot be accomplished without what Ausubel, (2000) termed meaningful learning. If procedures are learned meaningfully with appropriate connections, they are then linked to conceptual knowledge; however, if procedural knowledge is learned decontextualized from relationships it is restricted to a specific context and is not easily transferred to other situations (Hiebert & Lefevre, 1986). With conceptual knowledge, the learner not only knows what to do using procedural knowledge, but also why they are doing it.

Definitions of Knowledge Used in This Study

There is little agreement in the research literature with regard to the definitions of terms used for knowledge and understanding. For example, Gott and Duggan (2002) organized factual learning with conceptual understanding, and algorithmic skills with procedural understanding. Mayer (2008) created separate categories for factual, schematic, conceptual and procedural knowledge. Both Gott and Duggan (2002) and Mayer (2008) presented procedural knowledge at a higher level of learning than conceptual knowledge. Anderson and Krathwohl (2000) and Meltzer (2007) used separate categories for factual and procedural knowledge. Ausubel (2000) used the term representational learning for factual learning and propositional learning for understanding how concepts were related. Additional types of knowledge have been categorized. For example, conditional knowledge (Nieswandt, 2007) and metacognitive knowledge (Meltzer, 2007) have been used to refer to knowledge about how to go about solving problems. The delimitation of this research to procedural and conceptual knowledge was to be consistent with the type of knowledge prevalent in the science and mathematics literature related to problem solving and these terms were defined in the previous chapter and in Figure 1-1 (see p. 10).

Skemp (1978) analyzed the merits of procedural and conceptual knowledge for mathematics education. For simple, algorithmic problem solving, procedural knowledge was more efficient and provided immediate rewards, whereas conceptual knowledge was more adaptable to new tasks and increasing task complexity. Among the benefits of meaningful learning, linking procedural knowledge with conceptual knowledge (see Figure 1-1), are better retention of information because of cognitive changes in the learner's memory system, and easier transferability of procedures to new contexts (Mayer, 2008). For example, students may be expected to remember that both cations and electrons move towards the cathode. A procedural knowledge assessment item for this information may ask students to identify facts such as what moves towards the cathode, whereas a conceptual knowledge question would ask for an explanation of why the movement occurs. According to cognitive scientists, people have procedural knowledge abilities that are essential for processing information and acting successfully in different environments. One of these abilities is pattern matching, the act of checking for the presence of the constituents of a given pattern. The ability to quickly "settle" on an interpretation of an input pattern is central for perceiving, remembering, and comprehending (Rumelhart, Smolensky, McClelland, & Hinton, 1986) and serves to reduce the working memory requirement for a task. Cognitive science does not deny that procedural knowledge is important for thinking and problem solving but research on expertise in areas such as chess, history, science, and mathematics demonstrates that experts' abilities to think and solve problems depend strongly on a rich body of knowledge about subject matter (e.g., Chase & Simon, 1973; Chi, Feltovich, & Glaser, 1981). The research shows that "usable knowledge" is not the same as a mere list of disconnected facts. Experts' knowledge is connected and organized around important concepts (e.g., kinetic molecular theory, or patterns of chess moves); it is structured to specify the contexts in which it is applicable; and it supports meaningful learning that transfers to other contexts, rather than only the ability to remember (Barnett & Koslowski, 2002). For example, students who are knowledgeable about particles, such as electrons in an electrochemical cell, know more than facts about the direction of particle movement; they also understand why the particles have particular properties. They know that an electrochemical cell contains two half-cells each containing a solid electrode and a conducting solution. The substances in the half-cells have different abilities to attract electrons. The oxidizing agent, which is in the half-cell containing the cathode, has a stronger attraction to electrons than the reducing agent, which is typically the solid electrode in the anode half-cell. The electrons travel through a wire connecting the two substances and change the chemical properties of the oxidizing agent by causing it to be reduced. The movement of electrons in this direction causes the cathode to have a relative negative charge compared to the anode which in turn attracts positive ions causing them to move through the electrolyte towards the cathode. Because they understand the relationships between the structure and function of electrochemical cells, knowledgeable individuals are more likely to be able to use what they have learned to solve novel problems—to show evidence of transfer. Asking questions that require students to design, compare, or evaluate does not guarantee a correct answer, but it does support thinking about alternatives that are not readily available if one only memorizes facts (Bransford & Stein, 1993). Indeed, Koslowski (1996) concluded that for students to achieve scientific understanding both data and the theory of underlying mechanisms are needed for successful causal reasoning.

Examining expertise can provide insights into the nature of thinking and problem solving. It is not simply general abilities, such as memory or intelligence, nor the use of general strategies that differentiate experts from novices. Instead, experts have acquired extensive knowledge that affects what they notice and how they organize, represent, and interpret information in their environment (Barnett & Koslowski, 2002; Bransford et al., 1999). This, in turn, affects their ability to remember, reason, and solve problems. Experts' knowledge cannot be reduced to sets of isolated facts but instead, reflects contexts in which these facts can be applied (Barnett & Koslowski, 2002). The categories of novice and expert; however, are not necessarily discrete. These categories can more realistically be considered as part of a continuum that represents increasing experience with the problems and their contexts in a field of study.

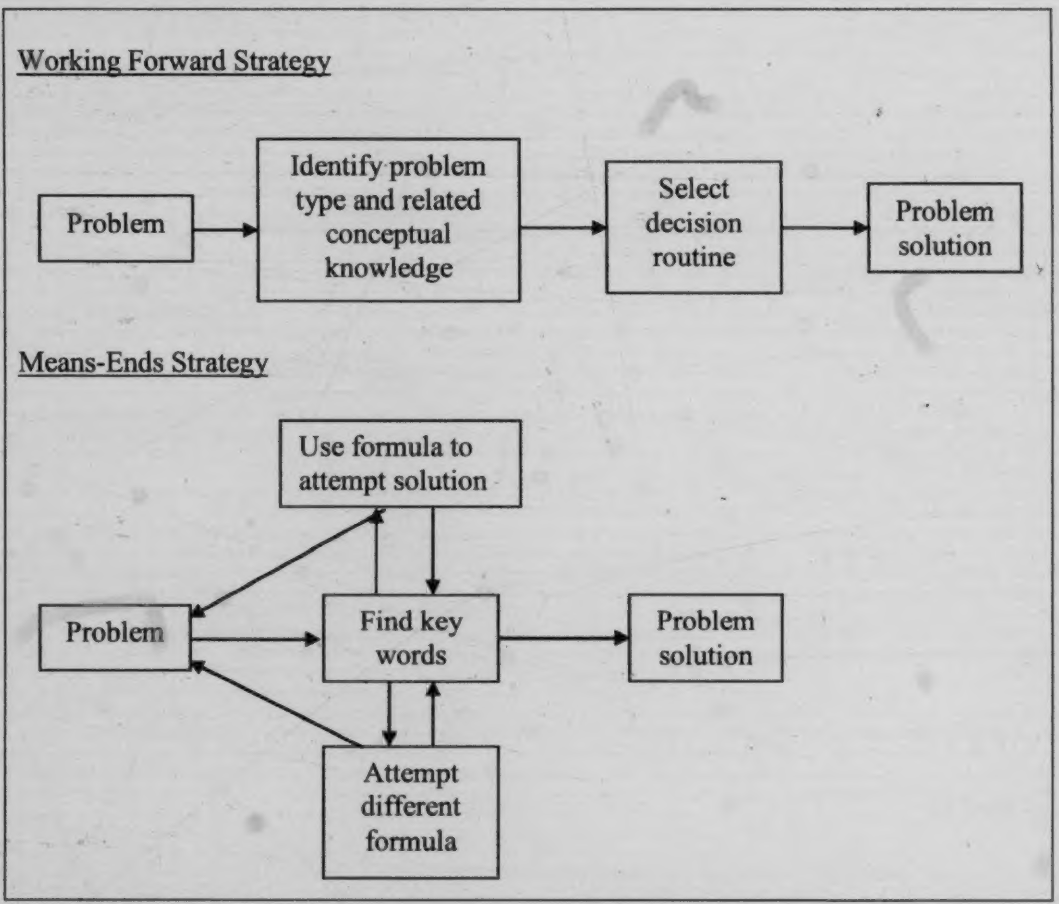
Problem Solving Strategies

Research in problem solving in science has predominantly focused on quantitative problems involving formulas and mathematical solutions (DiLisi, Eulberg, Lanese, & Padovan, 2006; Gangoso, Moyano, Buteler, Coleoni, & Gattoni, 2006; Heyworth, 1999; Koedinger & Nathan, 2004; Lyle & Robinson, 2001; Pushkin, 2007; Toth & Kiss, 2005).

Some basic mental processes have been identified in problem solving by researchers in the field of information processing psychology (Newell & Simon, 1972). One process is to construct representations of the problem based on conceptual knowledge of the problem and this has been called the "working-forwards strategy". A second process, called the "means-ends analysis strategy", involves "the use of a strategy to guide the search for a solution procedure from the initial state of the problem (the information and data given) to the goal state (required answer)" (e.g., Larkin, 1983; Owen & Sweller, 1985; Sweller, 1988). Although there are a variety of problem solving strategies discussed in the literature, these two strategies are predominant in problem-solving research in science and mathematics and henceforth the discussion of problem solving strategies in this paper will be limited to the "working forwards strategy" and the "means-ends analysis strategy".

The working forwards strategy, which is used by experts such as university physics professors, is associated with previous experience in the type of problem encountered. The strategy begins with the current information in the problem and works forwards performing operations until the solution is found (Larkin, 1983). Means-ends analysis has been associated with novice problem-solving and involves recursive forward and backward steps to identify the difference between current information and the solution. The problem-solver attempts a variety of different strategies until a solution is found, or until no other methods are generated (Larkin, 1983; Sweller, 1988) (see Figure 2-1).

Figure 2-1. Problem-solving strategies


Working Forward Strategy
Problem
Identify problem type and related conceptual knowledge
Select decision routine
Problem solution
Means-Ends Strategy
Use formula to attempt solution
Problem
Find key words
Problem solution
Attempt different formula

Note: diagram developed by researcher to illustrate problem solving strategies described in the literature (Larkin, 1983; Owen & Sweller, 1985; Sweller, 1988)

In the physics studies of Larkin (1983), novices (undergraduate students) successfully used a means-ends analysis for problems perceived as easy but for problems perceived as difficult, some novices would alternate strategies in an attempt to solve the problem. The participants in this study are novice problem-solvers in electrochemistry; however, the strategy that they use to approach problems may provide insight into the type of knowledge, procedural or conceptual, that they are using when solving problems. Studies in physics have shown that the representation of a problem changes while it is being solved and that these changes are different for experts and novices with initial attention directed to some of the key words in the problem (Chi et al., 1981; Larkin, 1983). This information is closely tied to real, familiar objects and forms part of the initial representation of problems for both expert and novice problem solvers (e.g., Larkin, 1983; Slotta, Chi, & Joram, 1995). For quantitative problems, experts link this initial representation to laws and principles to build up a qualitative procedure for solving the problem and this representation is then used to formulate a mathematical representation by guiding the selection of appropriate mathematical formulas. Novices focus on the superficial aspects of the initial representation which enables the behavior of objects in a real situation to be simulated, but which provides little guidance in selecting principles for application.

In their comprehensive review of problem-solving research in chemistry, Gabel and Bunce (1994) suggested that one of the main reasons students have difficulties solving some chemical problems is that they lack understanding of the connectivity of the concepts needed to solve the problems. This causes them to rely more on procedural knowledge using decision routines or algorithmic problem solving that can be committed to memory (Bröder & Schiffer, 2006). Procedural questions can be answered by applying a set procedure to generate a response. The procedure may be of a quantitative nature, such as balancing the electrons in a chemical reaction or by using a formula to complete a calculation. Success with procedural problem-solving can be achieved through rote-learning of the procedure to answer the question. Conceptual questions try to tap into the "why" aspect of a response that indicates meaningful learning of chemical ideas associated with the questions. They may be quantitative in nature where multiple approaches are possible, or qualitative requiring students to relate different ideas. This is a highly valuable form of assessment because teachers can probe the level of student learning while diminishing the value assigned to procedural knowledge.

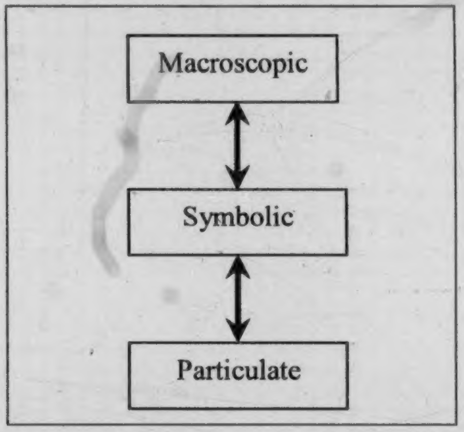
Category II. Levels of Representation of Knowledge

In chemistry, Johnstone (1991) has proposed that there are three levels of representation of knowledge:

- macroscopic, which deals with substances and their properties, and tactile manipulations in science such as the use of laboratory equipment
- particulate, which involves microscopic, molecular, atomic and subatomic entities, such as electrons and ions
- symbolic, which involves the use graphs, diagrams, tables, pictures, symbols, formulas and equation manipulation.

The ability to move among the three levels of representation would indicate conceptual knowledge in chemistry and de Jong and van Driel (2001) proposed that representations at the symbolic level form an important role at the macroscopic-particulate interface (see Figure 2-2). Without this interface, students may be able to demonstrate knowledge by the use of a redox table to predict observations in electrochemical cells, or have procedural knowledge of particle movement, but may have difficulty explaining why or how the cell operates without the ability to move between the three levels of representation.

Figure 2-2. Three levels of representation of knowledge in chemistry



Note: Developed from textual description in de Jong and van Driel (2001)

Category III. Alternative Conceptions

Students may come into science class with a set of non-scientific beliefs that they are unwilling to discard, despite evidence to the contrary. These may be false concepts or alternative conceptions that can be deeply ingrained in the mental map of an individual and hinder further learning when at odds with basic concepts. The task of overcoming alternative conceptions involves becoming aware of them, considering alternative conceptions or explanations, making a personal evaluation of the two competing ideas, and adopting a new conception as more reasonable than the previously held conception. This process involves self-reflection, critical thinking, and evaluation. By understanding the implication of alternative conceptions on the learning process and using methods that could diagnose and remediate them, teachers may increase their students' conceptual knowledge. In the following sections alternative conception research, both in science and more specifically in electrochemistry, will be discussed. The use of a diagnostic instrument as a tool to identify alternative conceptions will also be explored.

Alternative Conception Research

Science educators are paying increasing attention to students' learning of scientific concepts. Students enter their classrooms with ideas about science that have been influenced by their prior experiences, textbooks, teachers' explanations, or everyday language but which may not be in alignment with accepted scientific beliefs (Wandersee et al., 1994). These different concepts have been variously described by researchers as naïve beliefs (Caramazza, McClosley, & Green, 1981), preconceptions (Driver & Easley, 1978; Novak, 1977), children's science (Gilbert, Osborne, & Fensham, 1982; Osborne & Freyberg, 1985), intuitive beliefs (McCloskey, 1983), alternative frameworks (Arnaudin & Mintzes, 1985; Driver, 1981; Driver & Erickson, 1983), students' errors (Fisher & Lipson, 1986), alternative conceptions (Cho, Kahle, & Nordland, 1985; Driver & Easley, 1978; Fisher, 1985; Griffiths & Grant, 1985; Helm, 1980) and students' descriptive and explanatory systems (Champagne, Gunstone, & Klopfer, 1985). Students at all levels, and even science teachers, hold alternative conceptions; knowledge that is inconsistent with, or different from, scientific consensus and which may inadequately explain observable phenomena (Bodner, 1986; Cho et al., 1985; de Jong et al., 1995). Throughout this dissertation, the term alternative conception will be used to refer to students' conceptions that are different from the commonly accepted scientific understanding of the term. This term is often preferred because it is seen to express something of the status that many of these alternative ideas are said to deserve from a constructivist perspective (Taber, 2001). Once integrated into students' cognitive structure, alternative conceptions interfere with subsequent learning. Students are then left to connect new information into a cognitive structure that already holds inappropriate or incorrect knowledge. Thus the new information may not be connected appropriately to their cognitive structure and weak understandings or misunderstandings of the concept may occur, thus limiting successful learning in the field of study.

We cannot promote scientific learning and understanding without grasping the depth and tenacity of the student's alternative conceptions (Carey, 1986) because "the single most important factor influencing learning is what the learner already knows" (Mintzes & Wandersee, 1998, p. 81). Much of the research in this field has focused on the identification of students' alternative conceptions in various science concepts, and the majority of these studies have been carried out in situations outside the everyday classroom environment (Morrison & Lederman, 2003). Many methods have been proposed for teachers to use to identify their students' alternative conceptions, for example, concept maps, Vee diagrams, interviews, discussions, small group work, specific activities, journal writing, and paper-and-pencil tests (Mintzes, Wandersee, & Novak, 2000; White & Gunstone, 1992). Arising from this research has been a number of proposed learning models (Osborne & Wittrock, 1983; Posner et al., 1982) and specific recommendations for instructional strategies. These recommendations, however, may be difficult to actually carry out in the classroom. For example, in-depth interviews with individual students are often too time-consuming for teachers to employ during their regular class schedules. According to Duschl and Gittomer (1991), the reality of the classroom climate and culture seems to be often ignored in these models. It remains that in spite of these difficulties, the diagnosis of students' alternative conceptions may be the essential first step in facilitating the development of conceptual knowledge.

There is renewed interest in constructivist research as it attempts to put increasingly more emphasis on how conceptual development of cognitive structures may be facilitated rather than just identifying the alternative conceptions students possess (Valanides, Nicolaidou, & Eilks, 2003). Research reports indicate that teachers are not usually aware of students' difficulties in learning science subject matter, and in many cases, they exhibit alternative conceptions similar or identical to those of their own students (de Jong, 2000; Goodwin, 2000; Valanides, 2000a; 2000b). According to Talanquer (2006), most teachers are interested in the analysis and discussion of research results on students' alternative conceptions in chemistry but are overwhelmed by the number and diversity of alternative conceptions that science students have (e.g., Duit, 2007). Most of the alternative conception literature in chemistry traditionally organizes the information by topic or subject, but this "inventory approach" makes it difficult for teachers to identify any common assumptions or patterns of reasoning that may be guiding students' thinking in their classrooms about chemical phenomena. The development of such a common "explanatory framework" may be very useful to help chemistry teachers to identify, understand and even predict the possible alternative conceptions that their students hold (Talanquer, 2002). Such a system could allow teachers to organize the important knowledge about student ideas in chemistry in more meaningful ways. Nakhleh (1992) recommended that, based on her study of student alternative conceptions about the particulate nature of matter, questions be included on examinations that specifically probe for alternative conceptions. This could enable teachers to have a more accurate estimate of students' actual cognitive structures and encourage students to focus on the meaningful learning of concepts.

Alternative Conception Research in Electrochemistry

Students and teachers in the United Kingdom (Bojczuk, 1982), the United States (Finley et al., 1982; Sanger & Greenbowe, 1997a; 1997b), Australia (Butts & Smith, 1987) and the Netherlands (de Jong, 1982) ranked electrochemistry as one of the most difficult topics in chemistry. The literature provides us with a rich knowledge base of students' alternative conceptions in this field that has been compiled through student interviews and textbook analysis.

Some authors have identified the main sources of alternative conceptions as inconsistent terminology during instruction and in textbooks that leads to generalizations or overgeneralizations by students (Ambibol, Olakanmi, & Salihu, 1996; Pedrosa & Diaz, 2000; Ogude & Bradley, 1996). Three examples that are specific to electrochemistry follow.

Example 1: The position of the cathode in the half-cell on the right or the left in an electrochemical cell is arbitrary. The alternative conception that electrodes can be identified by their position in the cell is supported by teachers and texts that consistently depict the anode on the left side of diagrams.

Example 2: A spontaneous reaction can be predicted when the calculated difference between the cathode and anode half-cell potentials is a positive value. The alternative conception that half-cell potentials are absolute in nature and can be used to predict the cell spontaneity is supported by statements such as half-reactions with positive reduction potentials are spontaneous. This is further supported by explaining cell potentials by addition, $E^\circ_{cell} = E^\circ_{reduction} + E^\circ_{oxidation}$, which imparts significance to individual half-cell potentials. In fact, only the potential difference between two half-cells has meaning since absolute half-cell potentials cannot be measured, but are determined in relation to the standard hydrogen electrode.

Example 3: Electrons move through the wire in electrochemical cells as the wire connects two cells with an electrical potential difference between the anode and cathode reactions. Ions move through the electrolyte between the two half-cells in order to maintain electrical neutrality in the electrolyte. Statements and diagrams found in some textbooks about the presence of free electrons in the electrolyte solution and the transport of electrical charge by ions support other alternative conceptions (Sanger & Greenbowe, 1999).

Ogude and Bradley (1994) found that although many students can solve quantitative electrochemical problems on exams, few were able to answer qualitative questions requiring a deeper conceptual knowledge of electrochemistry. In a summary of research articles, de Jong et al. (1995) concluded that the main learning problem concerned both concepts and procedures. An example of a concept evoking learning problems is the relative strength of oxidizing and reducing agents while an example of a procedure evoking learning problems appeared to be classifying reactions as examples of redox reactions. However, it is important to differentiate among alternative conceptions, a lack of knowledge, and language problems in order to appropriately use conceptual change strategies (Clerk & Rutherford, 2000).

With the extensive inventory of electrochemistry alternative conceptions currently compiled, it is possible to focus research efforts on identifying the sources of these alternative conceptions and devising strategies to prevent and reverse them. Conceptual change instruction (Posner et al., 1982; Roth, 1985), in which the instructor elicits and then confronts student alternative conceptions, may lead to a significantly lower proportion of students demonstrating electrochemical alternative conceptions. Indeed Huddle, White, and Rogers (2000) developed a conceptual change teaching model to address three alternative conceptions in electrochemistry and showed that demonstrating or allowing student manipulation of a model of an operating electrochemical cell corrected alternative conceptions in the majority of students. Burke, Greenbowe, and Windschitl (1998), using computer animations of the particulate level of representation and a teaching approach that confronted student alternative conceptions, dramatically decreased the proportion of students consistently demonstrating the alternative conception that electrons can travel through aqueous solutions. Before teachers can envision teaching strategies to address their students' alternative conceptions, they must first identify them, devise teaching strategies to address them, and at the same time motivate their students to accept a change in their thinking.

Diagnostic Instruments

A number of tests developed as diagnostic instruments in science have been reported in the literature. Tests to identify alternative conceptions have followed a number of formats: open-ended response, multiple-choice knowledge questions with open-ended reasoning (Berube, 2004; Sexena, 1991), assertion-reason statements and a set of true-false alternative answers (Ozkaya, 2002), and multiple-choice with alternative conceptions as distractors (Hestenese, Wells, & Swackhamer, 1992; Mulford & Robinson, 2002). Tests to diagnose alternative conceptions can be two-tiered (Peterson & Treagust, 1989; Treagust, 1988): the first tier of each question based on procedural knowledge and the second tier based on a reason for the choice in the first tier. A student's answer to a two-tiered item is considered to be correct if the student selects both the correct content choice (procedural knowledge) in the first tier and the correct reason (conceptual knowledge) in the second tier. Analysis of incorrect response combinations provides data on student alternative conceptions of concepts related to that item. Ordered multiple-choice choice items (Briggs, Alonzo, Schwab, & Wilson, 2006) can also be used to gather formative information about students' conceptual knowledge for topics that reoccur in curriculum in different grades in increasingly complex reiterations.

One of the most important products of the research efforts on students' alternative conceptions in science has been a range of diagnostic assessment tools that focus on a single concept or a small set of related concepts (Wandersee et al., 1994). Many of these instruments employ traditional psychometric approaches such as multiple-choice items (Sadler, 2000), but differ from conventional tests in that the items reflect what students themselves understand about a scientific idea. The development of a diagnostic tool for this research project that could help to identify students' alternative conceptions in electrochemistry could have a number of positive influences. It was developed to be specific to the Alberta *Chemistry 30 Program of Studies* which includes most of the electrochemistry concepts identified by Garnett and Treagust (1992a; 1992b; see Appendix A). The items were a two-tiered format to determine the level of correspondence of students' procedural knowledge and conceptual knowledge of electrochemistry. This tool could be used in the diagnosis of students' alternative conceptions in electrochemistry, which may be the essential step required to make this field of study more accessible to high school students. The development of teaching strategies to address alternative conceptions may lead to students relying less on procedural knowledge and the rote following of procedures, and promote meaningful learning and understanding of the concepts of electrochemistry.

Summary

This chapter has discussed the constructivist perspective on learning and outlined the three categories in the framework of analysis used in this study: types of knowledge used in problem solving, levels of representation of knowledge in chemistry, and alternative conceptions. As has been outlined in this chapter, the three categories have been reported previously in the literature in studies that focused on either one or two of the categories. In studies exploring two categories, one of the three levels of knowledge representation (i.e. particulate) has been related to either problem solving or alternative conceptions. The aim of this study was to contribute evidence of students' understandings at the end of a unit of study in electrochemistry and the exploration of the three categories used in the framework of analysis and their inter-relationship could contribute to our insight into the complexity of the learning process for high school students in this field of study.

CHAPTER III

RESEARCH PROCEDURES

Research Perspective

> Because one cannot directly perceive students' mental processes, one must rely on less direct methods to make judgments about what they know (Pellegrino, Chudowsky, & Glaser, 2001. p. 36).

Despite the best efforts of teachers and curriculum designers, electrochemistry is found to be a very challenging field of study for high school students. As discussed in the introduction to this dissertation, my research was concerned with exploring students' understandings in electrochemistry at the end of a unit of study in order to develop a better understanding of why this topic is difficult for them. In Alberta, the components and basic operation of electrochemical cells are introduced in grade 9, but this topic is not revisited until grade 12. Students have limited exposure to the concepts involving electrochemical cells in their daily lives, although the use of these cells in the form of batteries is common. The information about this topic is, therefore, predominantly derived from school science.

Introduction

One aim of this study was to collect rich descriptions of students' knowledge and difficulties in electrochemistry and to identify what information students attended to during learning in this unit. Using Peshkin's (1993) categorization, the type of outcomes for this study were both description and interpretation. It was a descriptive inquiry in that it explored the knowledge that students use to make sense of electrochemistry, and the relationship between their past and current knowledge and experiences. As an interpretive inquiry it may "provide insights that change behavior, refine knowledge or identify problems, by clarifying and understanding complexity" (Peshkin, 1993) because it may elaborate existing ideas about teaching and learning in this field. It may also engender new concepts and ways of looking at the complex processes involved in learning. The study is heuristic in that it may offer insights into students' explanations of phenomena and may identify plausible causes for these explanations. Consequently, the nature of the research question, the nonexistence of any controlled treatment, the desired end product, and the focus of the investigation ensure that mixed methods research, using a triangulation design, fulfilled the aim of this study (Creswell, 2002).

In mixed method research, both qualitative and quantitative methods of data collection are used. Creswell (2002) claimed, "It is advantageous to the researcher to combine methods to better understand a concept being tested or explored" (p. 177). Greene, Caracelli, and Graham (1989) proposed a number of purposes for mixing methods in a study. These included triangulation to seek convergence of results, emergence of overlapping and different facets of the phenomena, and an increase in the scope and breadth of the study. According to Greene et al. (1989), the intentional use of multiple methods helps to strengthen the validity of the research results through triangulation by using different methods to assess the same aspect of a phenomenon. Information from one source helps to interpret the meaning of information from another source (Krathwohl, 1998). Grey and Costello (1987) stated this idea clearly, "Qualitative methods can establish the degree to which perceptions are shared, but uncovering the perceptions themselves must be done naturalistically" (p. 12). In discussing the contrast between qualitative and quantitative designs, Leedy (1993) referred to the discovery orientation of qualitative research and the verification orientation of quantitative research. This was furthered by Creswell (2002) who described mixed method designs as an effective and efficient means of conducting research because the designs are technically adequate (reliable and valid), practical, and ethical. Each of these methods had inherent strengths and weaknesses, but by using a variety of methods I received information that ranged from very broad to very specific perceptions of the knowledge used by students and the difficulties that they encountered in the field of electrochemistry.

The study was comprised of two phases, a preliminary pilot study followed by the main study. An overview of the methods and types of data collection used in this study (see Table 3-1) and an overview of the timeline for the research (see Table 3-2) are given below.

Table 3-1. Quantitative and qualitative methods of data collection and types of data collected

Phase I: Pilot Study	
Methods of Data Collection	Types of Data Collected
Quantitative Research	
Diagnostic instrument	Numeric scores
Qualitative Research	
Semi-structured interviews	Transcription of student diagnostic instrument interview audio tapes
Phase II: Main Research Study	
Methods of Data Collection	Types of Data Collected
Quantitative Research	
Diagnostic instrument	Numeric scores Numeric scores for open response questions
Textbook analysis	Numeric scores
Semi-structured interviews	Numeric scores for levels of representation
Qualitative Research	
Classroom observations	Field notes
Student assignments, reports	Research notes
Semi-structured interviews	Transcription of student lab-based interview audio tapes
Semi-structured interviews	Transcription of student diagnostic instrument interview audio tapes
Teacher group interview	Transcription of teacher group interview audio tapes

Table 3-2. Timeline for the research

Phase I: Pilot Study	
Administration of diagnostic instrument	June 2006
Student interviews	June 2006
Phase II: Main Research Study	
Edmonton Catholic Schools	
Classroom observation	Dec. 2006
Administration of diagnostic instrument	Jan. 2007
Student interviews	Jan. 2007
Teacher group interview	Jan. 2007
Data analysis	Feb. – Mar. 2007
Edmonton Public Schools	
Classroom observation	May 2007
Administration of diagnostic instrument	May 2007
Student interviews	May 2007
Teacher group interview	June 2007
Data analysis	July – Aug. 2007
Analysis of aggregated data	Sept. – Oct. 2007

Pilot Study

To begin this research study a pilot study was conducted in two Chemistry 30 classes in an urban high school in Alberta. The students participating in the study were 17 and 18 years old and in their final semester in high school. The main goal of the pilot study was to evaluate the effectiveness of a diagnostic instrument in electrochemistry to identify students with specific alternative conceptions in relation to redox concepts and the operation of electrochemical cells. Twenty-three of 33 students in the two classes volunteered for the diagnostic instrument and six students volunteered to participate in interviews. During the interviews, students were probed for alternative conceptions, including some related to electrochemistry calculations that were not previously identified in the literature. The interview data collected during the pilot study was relevant to the main study and will be included where appropriate.

Development of the Pilot Diagnostic Instrument

A two-tiered test was constructed based on the format developed by Treagust (1988). The first tier of each pair of questions was based on procedural knowledge and the second tier was based on conceptual knowledge, with the student choosing a reason for their choice in the first tier. This type of questioning has the potential to distinguish between procedural knowledge and conceptual knowledge when examining student work (Treagust, 1988). It must be acknowledged that if a student developed a decision routine using conceptual knowledge, then with practice, the application of multiple steps to solve a problem may become procedural knowledge. If procedural knowledge is acquired in this way in conjunction with conceptual knowledge, then meaningful learning may result in understanding with good retention and good transfer performance (Mayer, 2008). The vocabulary, skills, and techniques which had been documented during the classroom observations assisted in classifying the types of knowledge used in the pilot study diagnostic instrument as either procedural or conceptual knowledge, as defined in the previous chapter.

An answer to a two-tiered item was considered to be correct if the student selected both the correct content choice (tier one) and the correct reason (tier two). The knowledge component in the first tier of the diagnostic instrument was obtained from previously administered questions from the Alberta Chemistry 30 diploma examinations (see Table 3-3) to ensure content validity. All tier-two questions were developed by the researcher. The large sample of students who wrote the diploma exams (8 000–10 000) ensured reliability, and the rigorous review of these questions by committees of teachers and chemistry professionals during the diploma exam development process ensured content validity of the tier one questions.

Table 3-3. Source of tier one questions for the pilot study diagnostic instrument

Pilot Question	Diploma Exam	Question Type	Diploma Exam Question
1-1	June 2003 (2)	MC	17
2-1	June 2001 (1)	MC	19
3-1	Jan. 2002 (1)	NR	10
4-1	June 2000 (1)	NR	7
5-1	June 1999 (1)	NR	7
6-1	June 2003 (2)	MC	23
7	June 2001 (1)	NR	7
8	June 2001 (1)	MC	18
9	Jan. 2002 (1)	NR	11
10	–	–	–
11	Jan. 2000 (1)	NR	6
12	Jan. 2002 (1)	MC	21

Note: MC – multiple choice, NR – numerical response
(1) Alberta Education (2008b), (2) Alberta Education (2005b)
Question 10 was not obtained from a previously administered diploma exam, but was developed by the researcher for a specific concept.

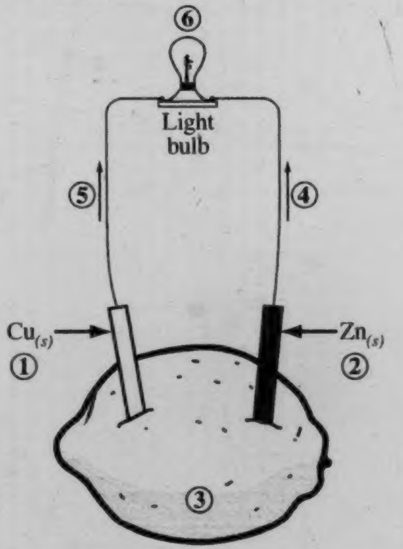
Conceptual knowledge questions in the second tier of the instrument were constructed based on a previously validated list of electrochemistry concepts (Garnett & Treagust, 1992a; 1992b; see Appendix A). Three experienced secondary school chemistry teachers and three chemistry professors validated this list of concepts to ensure that it represented the outcomes of the Alberta *Chemistry 30 Program of Studies* (Alberta Education, 2007a) and some modifications were made to make the electrochemical cell vocabulary specific to the Alberta program. For example, the term electromotive force was replaced with electrical potential. Alternatives to the correct answer were constructed using electrochemistry alternative conceptions identified in the literature (Garnett & Treagust, 1992a; 1992b; Sanger & Greenbowe, 1997a; 1997b; Ozkaya, 2002; see Appendix D).

In order to determine the best style of question to use for the two-tiered questions in the diagnostic instrument, five different formats were used in the pilot study: multiple choice to multiple choice, multiple choice to numerical response, numerical response to multiple choice, multiple choice to open response, and numerical response to open response. Multiple-choice to open-ended response combinations were used to probe for alternative conceptions related to electrochemical calculations which had not been reported in the literature. Knowledge outcomes in the *Chemistry 30 Program of Studies* (Alberta Education, 2007a) include calculating "mass, amounts, current and time in single voltaic and electrolytic cells by applying Faraday's law and stoichiometry" and "quantities of substances involved in redox titrations". The content validity of the diagnostic instrument questions was assessed by three experienced chemistry teachers and three chemistry professors prior to its administration. An example of a two-tiered question from the pilot study diagnostic instrument is given in Figure 3-1.

Figure 3-1. Two-tiered question 3 from the pilot study diagnostic instrument.

Use the following information to answer the next two questions.

A voltaic cell capable of lighting a small light bulb can be made by placing copper and zinc strips in a lemon.



Numerical Response

3-1. Identify the part of the voltaic cell, as numbered above, that corresponds to each of the descriptors listed below. Key: 2143

Anode __________ (Record in the **first** column)
Cathode __________ (Record in the **second** column)
Electron flow __________ (Record in the **third** column)
Electrolyte __________ (Record in the **fourth** column)

3-2. The anode in the electrochemical cell above is

A. identified by its location in the cell (8c)
B. the species with the highest reduction potential (8a)
***C.** the metal with the least ability to attract electrons
D. the metal that is listed highest in the standard reduction potential table (8b)

Note: The correct answer is indicated by an asterisk. The alternative conceptions used to develop the distractors are identified in brackets and explained in Table 3-4.

The source for question 3-1 was numerical response 10 from the January 2002 Chemistry 30 Diploma Examination. The keyed response was 2143 and the question had a difficulty of 68.4%. The keyed response for question 3-2 was C. The alternative conceptions that were used to develop the distractors for this question are given in Table 3-4, and Table 3-5 presents the cross-tabulation analysis of the aggregated data for this question.

Table 3-4. Alternative conceptions used to develop the distractors for question 3-2 for the pilot study diagnostic instrument.

Code	Alternative Conception Description	Literature Source
8a.	In standard reduction potential tables the species with the highest E° value is the anode.	Garnett & Treagust (1992a)
8b.	Standard reduction potential tables list metals in order of decreasing reactivity from the top down	Garnett & Treagust (1992b)
8c.	The identity of the anode and cathode depends on the physical placement of the half-cells	Ozkaya (2002)

Table 3-5. Cross-tabulation analysis table for two-tiered question 3 in the pilot study diagnostic instrument with multiple choice and numerical response combinations. Numbers represent student answers (n=23).

	Conceptual Knowledge (3-2)			
	A	B	C*	D
Procedural Knowledge (3-1)	**1253 (2)***	**1253*** 2143 (2) 2153	**1253 (4)*** 2143 (2) 1243 5463	**1253 (3)*** 2143 (2) 2146 2153 1254 1236
	8.7%	17.4%	34.8%	39.1%

Note: An asterisk indicates the correct response. A number in parentheses indicates multiple students recording the same response.

Summary: Of the ten students who responded correctly to procedural knowledge question 3-1, only 4 students also correctly answered conceptual knowledge question 3-2.

The twenty three students who volunteered to write the pilot study diagnostic instrument were asked to communicate the method used to answer each question and any comments about the questions. Each question was scored and open response questions were coded for level of learning in the responses using the scoring scheme in Table 3-6.

Table 3-6. Scoring scheme for responses on the open-ended questions in the pilot study diagnostic instrument

Code	Level of Learning	Criteria for scoring
1	No response	Responses left blank Responses that state or indicate, "I don't know" or "I guessed" or "I don't understand"
2	No understanding	Responses that repeat the question Irrelevant or unclear responses
3	Specific misunderstanding or alternative conception	Responses that include illogical or incorrect information
4	Partial learning with specific misunderstanding or alternative conceptions	Responses that show learning of the concept but also make statements that demonstrate a misunderstanding
5	Partial learning	Responses that include at least one of the components of the validated response, but not all the components
6	Meaningful learning	Responses that include all components of the validated response.

Adapted from: Abraham, M.R., Grzybowski, E.B., Renner, J.W., & Marek, E.A. (1992). The term understanding was replaced with learning or meaningful learning to align with the vocabulary used in this study.

Student Interview Format

Six students volunteered to participate in individual semi-structured interviews to probe their responses in the pilot study diagnostic instrument. In order to limit the time required for each interview (approximately 30 minutes), students were invited to discuss specific questions in which they correctly answered only one question in the pair of two-tiered questions or had included comments that required clarification. For example, a student may have answered procedural knowledge question 3-1 correctly but the conceptual knowledge question 3-2 incorrectly (see Figure 3-1). Thus during the interview, students were asked to discuss only 6 to 9 questions rather than all eighteen questions in the pilot study diagnostic instrument in order to ensure that an excessive time commitment was not required of them. At the beginning of each interview, I explained to students that I had not marked their answers correct or incorrect on their diagnostic instrument because I was interested in exploring the strategy that they used for answering the questions. I did offer to give them the results of the pilot study diagnostic instrument after the interview was completed and to answer any of their chemistry questions at that time.

For each two-tiered question selected for an interview, the student was asked, "Would you talk to me about how you approached answering this question?" This was followed by additional questions to clarify the student's explanations, to probe their learning of the concepts in the questions and to explore any alternative conceptions that arose. Sample interview questions used for question 3-1 and 3-2 (see Figure 3-1) are shown in Table 3-7. Each interview was approximately 30 to 45 minutes long and was conducted outside of class time. These interviews were audio recorded, summarized for research purposes, and selectively transcribed. This was done by eliminating student utterances that did not contribute to the understanding of the dialogue. For example, sounds that were made when thinking about a problem, such as um or ah were not included in the transcript.

Table 3-7. Sample interview questions used for questions 3-1 and 3-2 in the pilot study diagnostic instrument

1. What is the purpose of each piece of piece of apparatus shown here?
2. How would you determine which electrode is the anode and which electrode is the cathode?
3. What is happening in the electrolyte?
4. In which direction do the positive and negative charges flow in this cell to complete the circuit?
5. Why do charges flow in this circuit?
6. Can the electrode potential be determined in this cell?

Main Research Study

The main research study was conducted in seven classrooms in two large urban high schools and involved the participation of four teachers. To answer the research question, five different types of data were collected:

(1) Classroom observation of sixteen, 80-minute Chemistry 30 classes

(2) The examination of learning and teaching materials such as student notebooks, assignments, laboratory activities, demonstrations, computer animations, teaching videos, textbooks, and teachers' notes

(3) The results of a diagnostic instrument comprised of ten, two-tiered, multiple-choice questions to assess the level of procedural and conceptual knowledge in electrochemistry and to identify alternative conceptions

(4) A 60-80 minute audio-taped, task-based, semi-structured interview in the laboratory during the set-up and operation of electrochemical cells, and a 15-20

minute semi-structured interview to discuss the results of the main study diagnostic instrument

(5) An audio-taped group interview with teachers participating in the study to share the research results and discuss their ideas about how this information could inform teaching practice.

From a constructivist perspective, the students' chemical constructs represent the view of electrochemistry that they have constructed as they experienced it. It was thus important for me to become familiar with how students' experienced the information during this unit. Classroom observations, and the examination of student and teaching artifacts, as well as teaching resources such as textbooks, video, and laboratory materials were used to help me become familiar with the language and practices used during the unit and to provide a context for the analysis of the diagnostic instrument and during interviews. Additionally, the pre-interview activity, which was discussed before beginning the task-based interview, encouraged students to reflect on their problem-solving strategies and the sharing of their stories from this reflection provided some insight into their personal perspectives and learning style preferences. The research focused on student understandings at the end of a unit of study, hence conceptual change, neither hot nor cold, could not be addressed, as this type of research required longitudinal studies.

The Research Sites

The student participants in the main study were from two urban high schools, in classes in which students had a range of academic achievement. Both publicly-funded schools were comprised of grades 10 to 12 and offered a range of academic and non-academic courses. The student population was 1100 and 1600 in the two schools, which were located in diverse neighbourhoods that tended towards the upper-middle socio-economic class.

To minimize the impact of misunderstandings and alternative conceptions that might arise from individual teachers, the sample was selected from different schools and different classes rather than including students from only one setting. The two schools were selected because their teachers expressed interest in and volunteered to participate in the study, the geographical location of the school, and the availability of classes. At both schools, all the Chemistry 30 teachers and all of the grade 12 chemistry classes scheduled during the semester were involved in the study.

The Students

The students who volunteered to participate in the study were 17-18 years old and the majority of them were in their final year of high school. They had all chosen to study chemistry in grade 12. Eighty-seven of a possible 102 students from the seven classes volunteered to write the main study diagnostic instrument and nineteen students volunteered to participate in interviews.

A sample of nineteen was considered a reasonable size for the qualitative part of this study (Creswell, 2002). The in-depth interviewing needed for such a qualitative study was "not designed to test hypotheses, gather answers to questions, or corroborate opinions. Rather, it [was] designed to ask participants to reconstruct their experience and to explore their meaning. The questions most used in an in-depth interview follow from what the participant has said" (Seidman 1991, p.69) or communicated non-verbally during the task-based protocol. Therefore, interviewing a small number of students would provide a range of student responses and yield a manageable number of interviews to conduct, analyze, and interpret. In order to develop an in-depth understanding of a student's conceptual framework in electrochemistry, multiple forms of data were collected and this necessitated a small number of cases. According to Creswell (2000, as cited in Creswell, 2002), "providing this in-depth understanding requires studying only a few cases, because for each case examined, the researcher has less time to devote to exploring the depths of any one case" (p. 486).

The Teachers

Two teachers from each school with a range of teaching experience (see Table 3-8) were involved in the research study. Teachers' names were replaced with pseudonyms.

Table 3-8. Years of teaching experience for teachers involved in this research study.

School	Teacher	Teaching Experience
I	Mr. Clarke	3 years
	Mr. Smyth	> 25 years
II	Ms. Maloney	3 years
	Mr. Weber	> 25 years

The teachers volunteered to be part of the research study because they were interested in exploring why their students experienced a high degree of difficulty in electrochemistry.

The teachers made use of a variety of explanations and teaching strategies, choosing those most appropriate for the content and using a format to suit their students' learning styles. These teaching strategies included lecture, video clips of animations representing particle motion, laboratory activities, demonstrations, videos, note-taking, textbook reading and assignments, and worksheets. The four teachers were given a broad outline of the purpose of the study and were encouraged to teach in their normal style, despite the presence of a researcher in the classroom. I had previously worked with three of the four teachers on committees at the school board and provincial level. All teachers freely talked about their teaching philosophies and strategies.

Classroom Observations

Sixteen classes were observed during the study of electrochemical cells and the related concepts. At one school, this occurred at the end of the first semester and at the other school during the middle of the second semester. The classes to be observed were chosen to allow me to spend equal time with each teacher and to provide me with a chance to see a wide range of electrochemistry concepts and so become familiar with the vocabulary and procedures used during lessons and laboratory activities. I interacted with students in their classrooms during the teaching of this unit but since I was not the classroom teacher, my role was defined by my perceived needs of the student(s), the teacher(s), and myself. I was not only a participant researcher but also a resource person, interacting with students during their activities, providing materials when necessary, and helping them solve problems. For example when one group was repeatedly unable to obtain a voltmeter reading during their experiment setting up voltaic cells, I was able to point out the air bubble in the salt bridge that was preventing the operation of the cells. During the observations, I kept field notes documenting the lesson topics, methods of presentation of material, and the way the students interacted with the material, such as asking and answering questions, because such observations might allow me to make connections between student explanations and where these explanations came from. During lectures, I was periodically called upon by the teachers to answer questions. During laboratory activities, the teacher and I walked among the students observing individual groups as they interacted during the investigations. I observed students as a participant observer and therefore sometimes intervened if invited to or when I sensed a need to intervene. Other times I would intervene to get a sense of where students were going with their investigations.

Ostensibly, participant observation is a straight forward technique: by immersing themselves in the subject being studied the researcher is presumed to gain understanding, perhaps more deeply than could be obtained, for example, by questionnaire items. Arguments in favor of this method include reliance on first-hand information, high face validity of data, and reliance on relatively simple and inexpensive methods (Dewalt & Dewalt, 2001). The downside of participant observation as a data-gathering technique is increased threat to the objectivity of the researcher, unsystematic gathering of data, reliance on subjective measurement, and possible observer effects (observation may distort the observed behavior) (Dewalt & Dewalt, 2001). Participation is a form of investment of time, energy, and self, and as such it raises obvious questions of possible bias. However, defenders of participant observation find greater bias in allegedly neutral instruments such as survey questionnaires. These, they say, involve the imposition of an externally conceived "scientific" measuring device (the questionnaire) on individuals who do not perceive reality according to that external conception (Bruyn, 1966; Dewalt & Dewalt, 2001).

The instructional topics during my classroom observations are presented in Table 3-9. The learning and teaching artifacts that were collected with permission from the students and teachers during the study are documented in Table 3-10.

Table 3-9. Summary of lesson topics and activities during classroom observations

- Using the redox table to write equations and predict spontaneity of reactions
- Laboratory activity to determine the spontaneity of reactions
- Writing and balancing redox equations
- Voltaic cell structures and their function
- Building a voltaic cell demonstration
- Video of voltaic cell functions and applications
- Video clip showing animation of electron and ion movement in voltaic cells
- Calculating net cell potentials for voltaic cells
- Laboratory activity to determine the voltage produced in four different voltaic cells (activity included a copper-zinc voltaic cell)
-
- Building an electrolytic cell demonstration (electroplating)
- Calculating net cell potentials for electrolytic cells
- Laboratory activity on electroplating an object
- Redox stoichiometry
- Corrosion and its prevention

Table 3-10. Summary of learning and instructional materials collected during the study

Student and Teacher Notes
- Teacher PowerPoint slides on electrochemistry concepts
- Student classroom notes

Assignments
- Drawing and labeling voltaic cell diagrams
- Drawing and labeling electrolytic cell diagrams
- Writing net cell equations and calculating cell potentials worksheet

Laboratory Reports
- Laboratory assignment on spontaneity of reactions
- Laboratory assignment on voltaic cells

Tests and quizzes
- Quiz on drawing and labeling voltaic cells
- Chapter test on electrochemistry concepts
- Unit test on electrochemistry concepts, voltaic cells, and electrolytic cells

Diagnostic Instrument

The most common approaches for obtaining information in alternative conception research are through interviews with students and/or open-ended responses to questions. Classroom teachers, however, often do not have the time, facilities or training to interview students effectively. One way to increase the classroom application of alternative conception research is to develop diagnostic tests (Treagust, 1988) that specifically probe for alternative conceptions. This could enable teachers to have a more accurate estimate of students' actual cognitive structures and encourage students to focus on meaningful learning of concepts (Nakhleh, 1992). A reliable and valid, pencil-and-paper, easy to score, test instrument could be a valuable tool for classroom teachers.

Changes to the Main Study Diagnostic Instrument Resulting from the Pilot Study

The pilot study diagnostic instrument (see Appendix B), that was developed by the researcher, was refined to address issues identified during that study. The three teachers who validated the pilot study questions and discussed the analysis found question combinations involving both numerical response and multiple choice time-consuming to analyze because they generated a large number of possible combinations of answers and so useful information was difficult to extract in a timely manner. Additionally, the open response questions did not identify alternative conceptions that were not already in the literature and so were not included. As a result of the recommendations from the teachers, only 5 of the 18 questions in the pilot study diagnostic instrument remained unchanged for the main study diagnostic instrument. The remaining questions were modified, rewritten or replaced (see Table 3-11).

Table 3-11. Description of how the questions used in the main study diagnostic instrument were changed from questions in the pilot study diagnostic instrument.

Main Study	Pilot Study	Description of Changes to Questions
1-1	2-1	No change
1-2	2-2	Alternative B reworded to reduce misinterpretation
2-1	1-1	New question written. Reduction half-reaction equation used with format similar to student data book. Data interpretation component of question replaced with a question requiring application of definitions.
2-2	1-2	NR changed to MC; new question written by researcher
3-1		New question written by researcher
3-2		New question from January 2001, MC 20
4-1	10	Modified by researcher with new information box containing fewer equations
4-2	11	Modified by researcher from NR to MC format with a new information box with fewer equations
5-1	5-1	NR changed to MC; new question from June 1999, MC 25
5-2	5-2	No change
6-1	4-1	New question from June 2003, NR 7 and modified by researcher to MC format
6-2	4-2	No change
7-1		New question from June 2000, MC 26; modified by researcher
7-2		New question written by researcher
8-1	12	Modified for a new equation and scenario
8-2		New question written by researcher to replace open response questions 7, 8 and 9 involving calculations requiring a mole ratio
9-1		New question written by researcher; diagram from June 2004, MC 25
9-2	3-2	Alternative D rewritten to reduce misinterpretation
10-1	6-1	No change
10-2	6-2	No change in wording; alternatives pyramided

Note: MC – multiple choice, NR – numerical response.
See Appendix B and C for the diagnostic instruments.

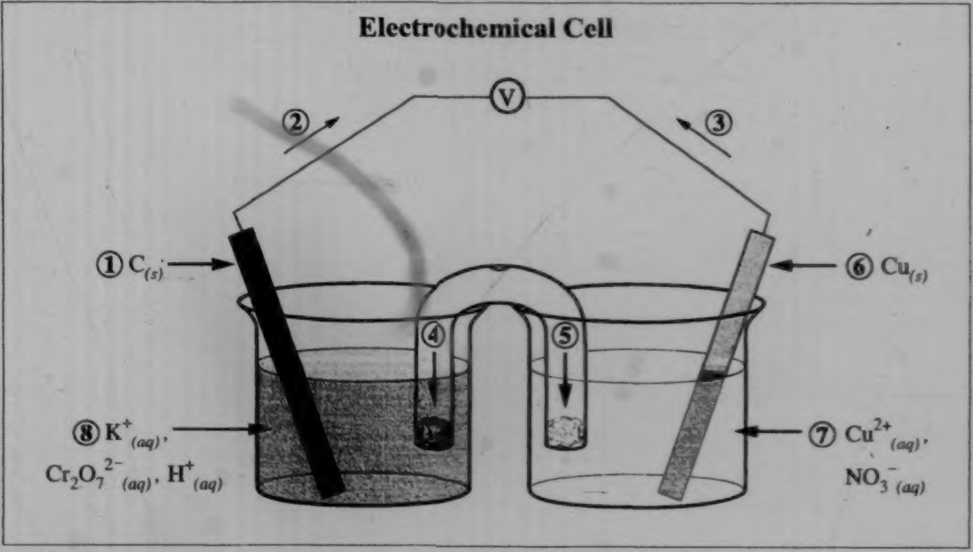
The teachers suggested that it would be easier to interpret the analysis tables (see Tables 3-12 and 3-13) if they were set up so that the first question for procedural knowledge was read down in columns and the second question for conceptual knowledge was read across in rows. It was also suggested that the alternative conception be identified in the table so that it was not necessary to use a second source of information to interpret the analysis.

The teachers discouraged the use of two tiered questions that contained multiple-choice and numerical-response combinations (see Figure 3-2), but preferred the multiple-choice to multiple-choice combinations (see Figure 3-3). They found that combinations that contained numerical response were time consuming to analyze and difficult to interpret efficiently. Mr. Clarke explained, "There are too many combinations of answers here for the numerical response questions. It will take me too long to record all the answers in the table and then I have to look up each combination to find out what the problems are" (see Table 3-12). Mr. Smyth explained that, "It is much easier to see what the students are doing from the tables that have only multiple-choice on them. Then each box in the matrix gives a specific piece of information so a pattern of problems is easier to see" (see Table 3-13). Since one of the goals of the pilot study was to develop an instrument that was easy to administer and analyze, it was decided to limit the two-tiered question format to multiple choice to multiple choice combinations.

Figure 3-2. Two-tiered question 4 in the teacher version of the pilot study diagnostic instrument

---

Use the following information to answer the next two questions.


Electrochemical Cell
V
②
③
① $C_{(s)}$
⑥ $Cu_{(s)}$
④
⑤
⑧ $K^+_{(aq)}$, $Cr_2O_7^{2-}{}_{(aq)}$, $H^+_{(aq)}$
⑦ $Cu^{2+}_{(aq)}$, $NO_3^-{}_{(aq)}$

Numerical Response

4-1. In the diagram above, the number that represents the Key: 6143

anode is __________ (Record in the **first** column)
cathode is __________ (Record in the **second** column)
cation flow is __________ (Record in the **third** column)
electron flow is __________ (Record in the **fourth** column)

4-2. Which of the following statements applies to the electrochemical cell in the diagram above?

A. Protons are attracted to the anode because it is negatively charged (8d, 11b)
B. Electrons are attracted to the cathode because it is positively charged (8d, 11a)
***C.** Cations move towards the cathode so that the cell remains electrically neutral.
D. Cations are attracted to anions in the electrolyte which limits their movement toward the cathode. (1a)

Note: The correct answers are indicated by an asterisk or by the key only in the teacher version of the diagnostic instrument. The alternative conceptions used to develop the distractors are identified in brackets and explained in Appendix D.

Table 3-12. Cross-tabulation analysis of question 4 in the pilot study diagnostic instrument related to a voltaic cell. The question was a two-tiered, numerical-response (4-1) to multiple-choice (4-2) format. The data represents the number of students selecting each alternative (n=23).

	Conceptual Knowledge (4-2)			
	A	B	C*	D
Procedural Knowledge (4-1)	8723	6143* 6135 6153 1653 1682 1672 2632	6143* (2) 6124 6133 6152 1652 (4) 1632 6853 8752	6143* (2) 6823
	4.3% (8d, 11b)	30.4% (8d, 11a)	52.2%	13.0% (1a)

Note: The correct answers are indicated by an asterisk. The alternative conceptions used to develop the distractors are identified in brackets at the bottom of the columns and explained in Appendix D. Of the five students who chose the correct response for procedural knowledge questions 4-1, two students also chose the correct response for conceptual knowledge question 4-2.

Figure 3-3. Two-tiered question 2 in the teacher version of the pilot study diagnostic instrument

---

2-1. The half-reaction to which all other half-cell potentials are compared is

- **A.** $Li^{+}_{(aq)} + e^{-} \rightarrow Li_{(s)}$
- **B.** $F_{2(g)} + 2e^{-} \rightarrow 2F^{-}_{(aq)}$
- ***C.** $2H^{+}_{(aq)} + 2e^{-} \rightarrow H_{2(g)}$
- **D.** $Au^{3+}_{(aq)} + 3e^{-} \rightarrow Au_{(s)}$

2-2. The reason why a standard half-cell is used is that

- ***A.** the designation of 0 V for the standard half-cell is arbitrary
- **B.** the reduction potential of a half-cell can be used to predict the spontaneity of individual half cells (9c)
- **C.** the designation of the standard half-cell is based on the chemistry of the components that make up the half-cell (9a)
- **D.** all half reactions that are listed above the standard half-reaction on a table of reduction half reactions will be spontaneous (9b)

Note: The correct answers are indicated by an asterisk only in the teacher version of the pilot study diagnostic instrument. The alternative conceptions used to develop the distractors are identified in brackets and explained in Appendix D.

Table 3-13. Cross-tabulation analysis of question 2 in the pilot study diagnostic instrument related to the reduction half-reaction table. The question was a two-tiered, multiple-choice (2-1) to multiple-choice (2-2) format. The data represents the number of students selecting each alternative (n=23).

		Conceptual Knowledge (2-2)				
Procedural Knowledge (2-1)		A*	B	C	D	
	A	0	1	0	1	8.7%
	B	0	0	0	0	0 %
	C	0	3	0	1	17.4%
	D*	11	4	1	1	74.0%
		47.8%	34.8% (9c)	4.3% (9a)	13.0% (9b)	

Note: The correct answers are indicated by an asterisk. The alternative conceptions used to develop the distractors are identified in brackets at the bottom of the columns and explained in Appendix D.

Three questions in the pilot study diagnostic instrument involved stoichiometry calculations. Each of these required writing an equation to represent the reaction, in addition to the calculation. As a result, it was difficult to determine from the students' multiple-choice answers whether the reason they were unable to solve the problem resulted from writing the equation or completing the calculation. To determine this, it was necessary to analyze the open-response question related to the procedural question and the student interview notes. For the main study, the teachers recommended that the stoichiometry questions be redesigned to include the equation and to incorporate alternatives that would provide information about whether the student was using mole ratios derived from the equation for the calculation.

Changes to the Main Study Interview Protocol Resulting from the Pilot Study

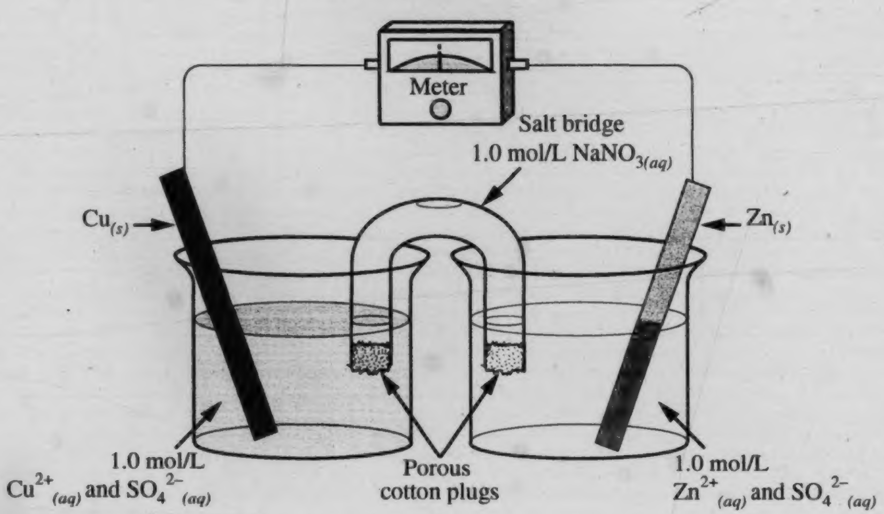
During the student interviews in the pilot study, a selection of laboratory equipment was available. Two of the six students interviewed used some of the equipment to help communicate their explanations about the operation of electrochemical cells rather than using the still diagrams in the pilot study diagnostic instrument. For example, for question 5-2 (see Figure 3-4), Kimberley placed a U-tube between two beakers when explaining why alternative A and B were not correct. Joanna used both the connecting wires and a U-tube as props when talking about the different pathways for electrons and ions. This appeared to facilitate some students' explanations, for example, when the name or function of a piece of apparatus could not be recalled, they could point to it or pick it up.

Figure 3-4. Two-tiered question 5 in the pilot study diagnostic instrument

---

Use the following information to answer the next two questions.

Electrochemical Cell


Meter
Salt bridge
1.0 mol/L $NaNO_{3(aq)}$
$Cu_{(s)}$
$Zn_{(s)}$
1.0 mol/L
$Cu^{2+}_{(aq)}$ and $SO_4^{2-}{}_{(aq)}$
Porous
cotton plugs
1.0 mol/L
$Zn^{2+}_{(aq)}$ and $SO_4^{2-}{}_{(aq)}$

Numerical Response

5-1. A student attempted to replicate a traditional Daniell Cell by setting up the electrochemical cell shown above. Under standard conditions, the electrical potential of the cell should be +/– __________ V.

(Record your **three-digit answer** in the numerical-response section on the answer sheet.)

5-2. In the electrochemical cell above electrons move through the

A. electrolyte because they are attracted to the positive ions in the solution

B. electrolyte in one direction and protons move through the electrolyte in the opposite direction

C. wire from the electrode with the lower reduction potential to the electrode with the higher reduction potential.

D. wire from the electrode with the high concentration of electrons to the electrode with the low concentration of electrons

---

Previous interview protocols reported in the literature that were used to explore students' alternative conceptions in electrochemistry involved the students discussing their answers using still diagrams (e.g. Garnett & Treagust, 1992b; Lin, Yang, Chui, & Chou, 2002). The results of the pilot study were used, therefore, to improve the nature of the interview to probe student knowledge. The interview was changed to a task-based format (Goldin, 2000) in a laboratory setting during which the students were asked to set up the electrochemical cells that were being discussed. Students were familiar with the electrochemical cells used in the task-based format from both laboratory activities and demonstrations that I had observed in their classes (see Table 3-9). Variations on the standard electrochemical cell set-up that were used to explore students' ability to transfer their knowledge to novel situations were based on the protocol of Lin et al. (2002). Their protocol was modified by replacing the still diagram of a copper-zinc voltaic cell with a cell that was assembled by the student in the laboratory.

Main Study Diagnostic Instrument

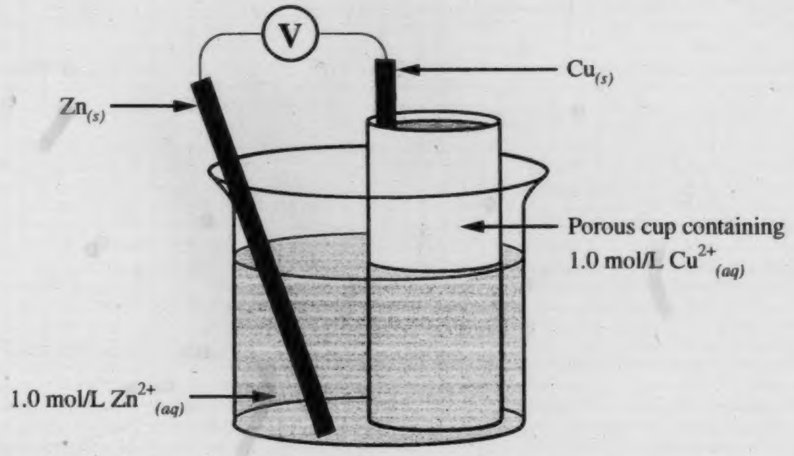
The main study diagnostic instrument consisted of 20 questions, designed as 10 two-tiered, multiple-choice to multiple-choice question combinations. Three experienced secondary school chemistry teachers and three chemistry professors reviewed the diagnostic instrument for reading level, graphics and science concepts, and validated it for content. A sample question is shown in Figure 3-5 and the diagnostic instrument (student version) is in Appendix C. The table used for cross-tabulation analysis of the group data for this question, and descriptions of the alternative conceptions used to develop the distractors, are in Table 3-14.

The main study diagnostic instrument was administered to 87 student volunteers in the seven classes. The administration occurred during one 80 minute class period under the test conditions typically used by their teachers, with students sitting at individual desks or at laboratory benches with barriers between them to block their view of adjacent papers. The students were given the test booklet and a chemistry data booklet (Alberta Education, 2008a). They were asked to complete all their work in the booklet and to transcribe their answers onto an answer sheet. The two-tiered questions were used to determine the correspondence between procedural knowledge and conceptual knowledge. Cross-tabulation analysis of the items in the diagnostic instrument was used to evaluate both correct and incorrect response combinations for each of the 10 pairs of questions. Analysis of incorrect response combinations provided data on students' alternative conceptions and analysis of correct responses provided data on students' problem-solving strategies.

Figure 3-5. Two-tiered question 5 in the teacher version of the main study diagnostic instrument

Use the following information to answer the next two questions.

Electrochemical Cell


V
Cu$_{(s)}$
Zn$_{(s)}$
Porous cup containing 1.0 mol/L Cu$^{2+}_{(aq)}$
1.0 mol/L Zn$^{2+}_{(aq)}$

5-1. The cell potential for the electrochemical cell in the diagram above is

***A.** +1.10 V

B. +0.42 V

C. –0.42 V (14a)

D. –1.10 V

5-2. In the electrochemical cell above electrons move through the

A. electrolyte because they are attracted to the positive ions in the solution (1b, 2e)

B. electrolyte in one direction and protons move through the electrolyte in the opposite direction (2d, 2e, 2f)

***C.** wire from the electrode with the lower reduction potential to the electrode with the higher reduction potential.

D. wire from the electrode with the high concentration of electrons to the electrode with the low concentration of electrons (3b, 3c)

Note: The correct answers are indicated by an asterisk. The alternative conceptions used to develop the distractors are identified in brackets and explained in Appendix D.

Table 3-14. Table used for the cross-tabulation analysis of the aggregated data for questions 5-1 and 5-2 (see Figure 3-5) in the main study diagnostic instrument with a description of the alternative conceptions used to develop the distractors

		Procedural Knowledge (5-1)					
		*A	B	C	D	total	Alternative Conception Description
Conceptual Knowledge (5-2)	A	7.0	1.1	0	1.1	9.2%	1b. Electrons move through electrolytes by being attracted to positive ions in solution. (1) 2e. Electrons flow in electrolytes. (1)
	B	3.4	0	1.1	1.1	5.6%	2d. Protons flow in electrolytes (regardless of whether the solution is acidic, basic or neutral). (1) 2e. Electrons flow in electrolytes. (1) 2f. Protons and electrons flow in opposite directions in an electrolyte. (1)
		58.6					Correct response. No alternative conception.
	D	18.4	0	0	1.1	21.8%	3b. There is a high electron concentration at the anode. (1) 3c. There is a low electron concentration at the cathode. (1)
	total	87.4%	2.2%	2.2%	7.9%		

Note: 5-1 B and C were based on alternative conception 14a. Cell potentials are derived by adding individual reduction potentials. (5)
(1) Garnett & Treagust (1992a), (5) Ozkaya (2002)

Format of Student Interviews

Pre-Interview Activity

The student was asked to complete a pre-interview activity focusing on their experiences with problem solving in order to "provide them with an opportunity to recall and select memories to share" prior to the interview (Ellis, 2006). When they selected an interview time, they were given a list of possible activities from which to choose (see Table 3-5).

They were asked to select on activity from the list and complete it before coming to their interview. Although this open activity may have taken the conversation in unexpected directions, it was thought to contribute to a holistic reconstruction of the student's experiences which might enable me to better understand their constructs in chemistry.

Table 3-15. A selection of pre-interview activities

Please choose **one** of the following activities to complete before our interview. The purpose of the activity is to allow you time to reflect on a time when you attempted to understand a new concept or solve a problem. This will provide us with a starting point for our interview.

- Draw a picture of yourself before and after trying to understand a new concept or solve a problem.

OR

- Make a list of key words that represent how you experience trying to understand a new concept or solve a problem.

OR

- Create a flow chart that shows the process that you would use when confronted with a new concept or when trying to solve a problem

OR

- Draw a timeline, and on it mark dates and titles of problems that you have solved that are important to you.

OR

- Draw a diagram that shows where you would access information that you would need to understand a new concept or solve a problem.

OR

- Draw a diagram and label it to show where your support systems come from when you attempt to understand a new concept or to solve a problem.

Task-Based Interviews

The interviews were held in a science laboratory outside of class time. Upon arrival, students were given an overview of the interview format, assured of the confidentiality of their interview, reminded that they could withdraw from the research project at any time, and asked for permission to audio tape the process. After donning safety glasses and a lab coat, we moved to a laboratory bench where two tape recorders and the materials and equipment listed in Table 3-16 were assembled.

Table 3-16. Materials and equipment available for student use during the task-based interviews about voltaic and electrolytic cells

Laboratory Materials and Equipment		
2 copper electrodes	porous cup	copper wire
2 zinc electrodes	glass U-tube	voltmeter
2 carbon electrodes	cotton balls	power supply
0.10 mol/L $CuSO_{4(aq)}$	steel wool	connection wires
0.10 mol/L $ZnSO_{4(aq)}$	250 mL beakers	paper
0.10 mol/L $KNO_{3(aq)}$	redox table	pencil

To begin the interview, students were invited to "Tell me about the activity that you selected for the pre-activity" (see Table 3-15). This allowed the students to become comfortable in the interview setting (Ellis, 2006). They were asked questions to allow me to understand their diagrams or descriptions and how these related to their learning and problem-solving strategies. See Table 3-17 for a list of sample questions used for the pre-interview activity.

Table 3-17. Sample interview questions about approaches to solving problems using the pre-interview activity

- What do you find most satisfying about solving a problem?
- What do you find most frustrating when solving a problem?
- What qualities make a problem challenging for you to solve?
- How would you describe your approach to solving a problem?
- Can you tell me about a problem that you solved of which you are particularly proud?
- What advice would you offer to someone who was confronted with a difficult problem to solve?

The purpose of the interview was to explore students' learning in electrochemistry and, in so doing, identify any difficulties or alternative conceptions. The interview protocol, developed by Garnett and Treagust (1992b) for identifying student alternative conceptions in electrochemical cells, was used with modifications. Instead of providing the student with still diagrams of electrochemical cells with a series of related questions, I used a task-based interview protocol (Goldin, 2000) with the predict-observe-explain (POE) model (White & Gunstone, 1992) using electrochemical cells assembled in a laboratory to observe and interpret scientific behavior. The semi-structured, task-based interviews consisted of the student and interviewer interacting in relation to activities, specifically the set-up and operation of voltaic and electrolytic cells. Instructions for the activities can be found in Table 3-18. According to Goldin (2000), in structured, task-based interviews explicit provision is made for contingencies that may occur as the interview proceeds, possibly by means of branching sequences of heuristic questions, hints, related problems in sequence, retrospective questions, or other interventions by the interviewer. My interest in the knowledge that students used while solving electrochemistry problems required a more open-ended interview protocol. Although a number of contingencies could be identified based on the inventory of electrochemistry alternative conceptions in the literature, a rigid, structured interview protocol would limit the probing of student meanings and understandings as the task progressed. Although Goldin's (2000) protocol was used in mathematics research, most of the research on problem-solving in science and chemistry has focused on quantitative problems. This approach may be suitable for studies about thinking, learning and/or problem solving in both chemistry and mathematics and from this I hoped to deepen our understanding of various aspects of science education by obtaining descriptive reports about the subjects' learning and/or problem solving.

The tasks around which the interviews were centered followed the protocol of Lin et al. (2002) for voltaic cells modified from their paper-pencil format using still diagrams of electrochemical cells to a laboratory activity. Materials were provided for the students to set up a copper-zinc voltaic cell and a copper electroplating cell (see Table 3-18).

The task protocol was comparable to that used by Valanides et al. (2003) in their action research project to improve teachers' knowledge of oxidation and combustion in which students were asked to predict, observe and then explain during the burning of copper and magnesium wires. Using the POE framework (White & Gunstone, 1992), students were instructed firstly to predict what would happen in the electrochemical cell, and then to set up the cell and make observations. Following each experiment, the students were asked to reflect on the correspondence of their predictions and observations. They were then asked to describe and explain the outcome of each experiment. Questions were raised concerning the consistency of students' predictions prior to each experiment and their explanations after it. This allowed me to elucidate the correspondence between their procedural and conceptual knowledge. A list of sample interview questions used for the task-based part of the interview is in Table 3-19.

During the interview students were asked to "self-explain", which involves spontaneously generating explanations to themselves (Chi et al., 1989), as they progressed through the POE framework. The focus of this verbal analysis method was to capture the representation of the student's knowledge and less on the processes of problem solving (Chi, 1997). One question that arises is the legitimacy of considering self-explanations as a source of verbal protocols because the process of generating self-explanations alters the processing of the to-be-learned materials. Self-explaining, whether prompted or spontaneous, is a process of reflection in which students are encouraged to reflect, think about, and infer while they are learning (Chi, de Leeuw, Chui, & Lavancher, 1994). The goal of the method is to attempt to figure out what a learner knows (on the basis of what a learner says, does, or manifests in some way, such as pointing or gesturing) and how that knowledge influences the way the learner reasons and solves problems, whether correctly or incorrectly. The learner's utterances could therefore be analyzed to capture the knowledge that might underlie those utterances and actions in a way that is quantifiable and not subjective (Chi et al., 1994).

Table 3-18. Laboratory instructions for the semi-structured, task-based interviews

Voltaic Cell Laboratory Instructions

1. Predict how a copper-zinc voltaic cell would be set up and how it would operate.

2. Set up the cell and record your observations.

3. Do your observations match your predictions?

4. Explain any discrepancies.

5. If both the copper and zinc electrodes are in one beaker that contains a solution of 0.10 mol/L $CuSO_{4(aq)}$, do you think the voltmeter will show a reading or not? Explain.

6. If the electrolyte in the beaker above is replaced with 0.10 mol/L $ZnSO_{4(aq)}$, do you think the voltmeter will show a reading or not? Explain.

7. If the salt bridge is removed, do you think the voltmeter will show a reading or not? Explain.

8. If the salt bridge is replaced with a copper wire, do you think that the voltage will be different from the voltage obtained when a salt bridge is used? Explain.

9. If the copper and/or zinc electrodes are replaced with similar carbon electrodes do you think that the voltage will change from that obtained with the copper-zinc voltaic cell? Explain.

Electrolytic Cell Laboratory Instructions

1. Predict how a copper electroplating cell would be set up and how it would operate.

2. Set up the cell and record your observations.

3. Do your observations match your predictions?

4. Explain any discrepancies.

Table 3-19. Sample interview questions during the task-based, semi-structured interviews during which students set up voltaic and electrolytic cells and made predictions and observations about their operation

- As you select the pieces of equipment that you would like to use to set up your electrochemical cell, could you tell me why you chose each one?
- How would you describe your approach to predicting how the electrochemical cell will operate?
- To what information do you pay attention when predicting how the electrochemical cell will operate?
- What do you think will change during the operation of the cell?
- What do you think will stay the same during the operation of the cell?
- In the cell that you are setting up, how would you determine which electrode is the anode and which electrode is the cathode?
- Will anything be happening in the cell that we are not able to see?
- In order to decide whether or not the cell is operating, what do you look for?
- After observing your cell operating, did any of your observations surprise you?
- When we replace the salt bridge with a piece of copper wire, what do you think will happen in the cell?
- Can we replace one or both of the copper and zinc electrodes with an inert electrode and still have a functioning cell? Explain what you think will happen.
- Can we operate the electrochemical cell in one beaker with only one of the electrolytes? Explain what you think will happen.
- Have you encountered a cell like this, and if so how might you use it?

During the interviews, I was a participant-observer (i.e. observed and participated with), in that I acted as a laboratory assistant to the student by providing an extra set of hands to hold or manipulate equipment while observing and posing probing questions. The limitations inherent with such an approach will be elaborated in Chapter III.

Diagnostic Test Interviews

Students were invited to discuss the results of the diagnostic instrument in an interview. Of particular interest were those questions in which there was a discrepancy between their procedural and conceptual knowledge. Students were also probed to determine if the alternative conceptions identified during their task-based interview were the same as those identified in the main study diagnostic instrument that they wrote. The source of alternative conceptions and problem-solving strategies were also probed during this interview. Additional questions, both correct and incorrect, were included in the interview. These included questions on which the students had made notations that needed clarification or if they had used methods that required further clarification to elucidate their thinking. See Table 3-20 for sample interview questions.

Table 3-20. Sample interview questions used to probe student problem-solving strategies and alternative conceptions for the main study diagnostic instrument interview

- Could you describe to me how you approach a problem like the one in this question?
- How did you decide that the other alternatives were incorrect?
- What information did you use to solve the question?
- Where did the information come from?
- Was there something in particular that makes this type of question difficult for you?

Teacher Group Interview

The following briefly outlines the structure of the teacher group interview. The group interview began with a short summary of the results of the main study diagnostic instrument and interview findings. Participants were assured of the confidentiality and anonymity of their remarks in the interview. To ensure that the discussion from the group interview was accurately documented, the participants were asked for permission for the discussion to be recorded on audio tape and I took notes during the proceedings. The tape helped with analysis and ensured accuracy of interpretation. The interview lasted about 1.5 hours. The session was focused by the questions in Table 3-21.

Table 3-21. Sample interview questions for the teacher group interview

- Did the students' use of knowledge in this study surprise you?
- Did any of the students' alternative conceptions surprise you?
- Can you share any ideas about how the alternative conceptions identified in this study may have developed?
- Are there different ways to address how students use knowledge or alternative conceptions?
- After looking at samples of student work related to conceptual knowledge from across the province in the Chemistry 30 Diploma Examinations during the marking session, what advice would you offer your students as they prepare for their exams?
- What advice would you offer other teachers who are currently teaching Chemistry 30?

Data Analysis

Alternative conception research has tended to focus on one variable rather than exploring the complex nature of learning. Sources of alternative conceptions have been identified using content analysis of textbooks, (Sanger & Greenbowe, 1999), observation of teaching practices (de Jong et al., 1995), and structured interviews using diagrams of electrochemical cells (Garnett & Treagust, 1992a; 1992b; Lin et al., 2002). By focusing on the collection of one type of data, these research approaches may not have produced the rich perspectives and valuable insights that could be uncovered with multiple forms of data and the use of multiple categories in the framework of analysis.

Research can be thought of as building layers of data which must be stripped away individually and then rebuilt in order to understand the parts and the whole of the process under study (Ellis, 1998). The collection of multiple forms of data (see Table 3-1) was an attempt to acknowledge that learning is influenced by many factors, not just the transmission of information from teacher to student. By analyzing the data using three categories in a framework of analysis, I attempted to understand the problem in a different way and attempted to see what went unseen before by re-examining the data for confirmation, contradictions, gaps, and inconsistencies (Ellis, 1998). Although the development of a diagnostic instrument fits more with the epistemological beliefs of rationalism rather than constructivism, its purpose was to develop a tool for classroom teachers with which to open conversations with students by acknowledging that their beliefs may differ from those of their teacher and through which they could explore student's procedural and conceptual knowledge. However, the use of this tool by the teachers in their classrooms was not a focus of this study. The validation of these interpretations was promoted by applying the constant comparative method (Denzin, 1994) or triangulation (Creswell, 2002). This involved the comparison of the analysis of the interview data with the other sources of data.

The audio tapes were analyzed by listening to them in their entirety for the first time to identify the three categories in the framework of analysis and then listening to them again noting passages for selective transcription. The categories in the transcriptions were identified by hand, using coloured tags. The other qualitative and quantitative data (see Table 3-1) were then analyzed using the coloured tags for the same categories. The process was then repeated to verify the data assigned to each category. The process used for the analysis of qualitative data is outlined in Figure 3-6.

One of the categories in the framework of analysis used in this study was related to the students' use of the three levels of representation of knowledge in chemistry: symbolic, macroscopic and particulate. A coding scheme was developed to quantify the students' use of the levels during the different aspects of the POE framework when analyzing the task-based interview data (see Table 3-22).

Table 3-22. Coding scheme and worksheet for the analysis of the use of the three levels of knowledge representation for the Predict-Observe-Explain (POE) framework used during the task-based interview

Code	Predict	Observe	Explain
S			
M			
P			
S + M			
S + P			
M + P			
S + M + P			

Categories for Analyzing the Three Levels of Knowledge Representation

Predict. The intent of the statement is to identify what will happen in the cell and occurs prior to the cell assembly.

Observe. The intent of the statement is to communicate information about what is currently happening in the cell as it operates. It will include statements related to data using the senses. Students may compare prior statements made during prediction.

Explain. The intent of the statement is to communicate information about what the student thinks is happening during the operation of the cell. Students may compare prior statements made during prediction and observation.

Symbolic. (S). The intent of the statement is to communicate information using the formal language of chemistry and may include, either orally or in text:

a. Chemical symbols including elements, ions and compounds
b. Chemical equations
c. Mathematical formulas
d. Numbers with units
e. Diagrams, labeled or unlabeled

Macroscopic. (M). The intent of the statement is to communicate information about observable properties and may include, orally or in text, statements about:

a. Changes in state or odours
b. Readings from equipment (e.g. voltmeter)
c. Changes in temperature
d. Changes in volume or size
e. Additional physical characteristics

Particulate. (P). The intent of the statement is to communicate information about the particulate nature of matter and may include, either orally or in text, statements about:

a. Cations or anions
b. Electrons, protons, or neutrons
c. Atoms, molecules, ions, formula units, elements, or compounds

Note: units of analysis represented complete statements by students.

Content Analysis of the Student Textbook

A coding scheme was used for two themes in the student textbook (*Nelson Chemistry*, 2003): the analysis of the relative emphasis of the interaction of science, technology, and society (STS) and for the investigative nature of science. The method to assess the curricular emphasis on STS interactions in science textbooks was developed by Chiapetta, Fillman and Sethan (1998) for the first four descriptors and the last three descriptors were developed from statements in the Council of Ministers of Education, Canada (1997). The descriptions used for the coding framework for levels of inquiry were developed by Bell, Smetana, and Binns (2005) (see Table 3-23).

The elements of the textbook (units of analysis) that were used in the content analysis for STS interactions included complete paragraphs, questions, figures, tables with captions, margin comments, and complete steps in laboratory or hands-on activities (e.g., problem, procedure). Pages that were not analyzed were those with fewer than two analyzable units and those that contained only review questions, vocabulary words, or goal and objective statements. Complete laboratory exercises in *Nelson Chemistry* (1993) were used as the unit of analysis for levels of inquiry and coded based on the descriptions in Table 3-23. The descriptors used allowed each laboratory activity to be assigned to a single category.

Table 3-23. Coding schemes used to analyze two themes in the student textbook, *Nelson Chemistry* (2003)

Interaction of Science, Technology and Society (STS)

Both science and technology are creative human endeavors with a long history in all cultures of the world. The intent of this category is to look at the nature of science and technology, the relationships between science and technology, and the social and environmental contexts of science and technology. This aspect of scientific literacy pertains to the application of science and how technology helps or hinders humankind. It involves social issues and careers. Nevertheless, the student receives this information and generally does not have to find out. Descriptors in this category are:

a) describes the usefulness of science and technology to society
b) stresses the negative effects or unintended consequences of science and technology
c) discusses the social issues related to science or technology
d) describes examples of science and technology-based careers
e) provides examples of how scientific knowledge has resulted in the development of technologies and how technologies have enabled scientific research
f) gives examples of scientific principles that have resulted in the development of technologies
g) describes issues related to science and technology, taking into account personal, community and environmental factors

Note: a) to d) from Chiapetta et al, 1991;
e) to f) developed from Council of Ministers of Education, Canada (1997)

Level of Inquiry of Laboratory Activities

Inquiry instruction is a method that can lead to development of scientific skills and problem solving abilities. The four levels of inquiry are:

I. **confirmation** of a principle through an activity in which the results are already known
II. **structured inquiry** using a prescribed procedure to investigate a teacher-presented question
III. **guided inquiry** using student-designed procedures to investigate a teacher-presented question
IV. **open inquiry** using student-designed procedures to investigate a student formulated question

Note: descriptions from Bell, Smetana, & Binns, 2005.

Progressively I developed a list of questions to keep in mind (see Table 3-24) as I collected and analyzed the different forms of data, e.g., as I observed students' engagement in the classroom and during the task-based interview, reviewed teaching and learning artifacts, prepared field notes, and talked to teachers. These questions helped to focus the analysis and served to validate the data. Individual questions served as a lens to focus attention on an aspect or pattern throughout all forms of data rather than analyzing the different data sources as discrete units. By using different methods to assess the same aspect of a phenomenon, information from one source of data helps to interpret the meaning of information from another source (Krathwohl, 1998) and this triangulation strengthens the validity of the research results.

Table 3-24. Questions used during analysis to identify categories and patterns in the data

Observational Questions Developed During Data Analysis

- Are the metaphors that teachers used misinterpreted by students?
- Are student metaphors different from teacher metaphors?
- Are there electrochemical words with both familiar and scientific meanings?
- Do students give definitions using scientific terms or everyday terms?
- What are the problem-solving strategies used by the students?
- Can the student's learning orientation (procedural/rote v conceptual/meaningful) be determined from their descriptions of their problem-solving strategy?
- Did students use the working forwards strategy (expert) for voltaic cells and means-ends strategy (novice) for electrolytic cells? (Heyworth, 1999)
- Was informal prior knowledge from everyday experiences or formal prior knowledge from school science used to explain electrochemical concepts?
- Is there a difference between student instrumental and relational understanding (Treagust et al., 2003)?
- At which level of chemical representation does the student prefer to operate and do they transfer among the three levels during predictions, observations or explanations or when solving problems?
- Are electrochemical principles generalized beyond the specific conditions under which they apply?
- How does using animations impact conceptual knowledge compared to using still diagrams?
- How does hands-on laboratory work impact conceptual knowledge compared to teacher demonstrations?

Validation of Data

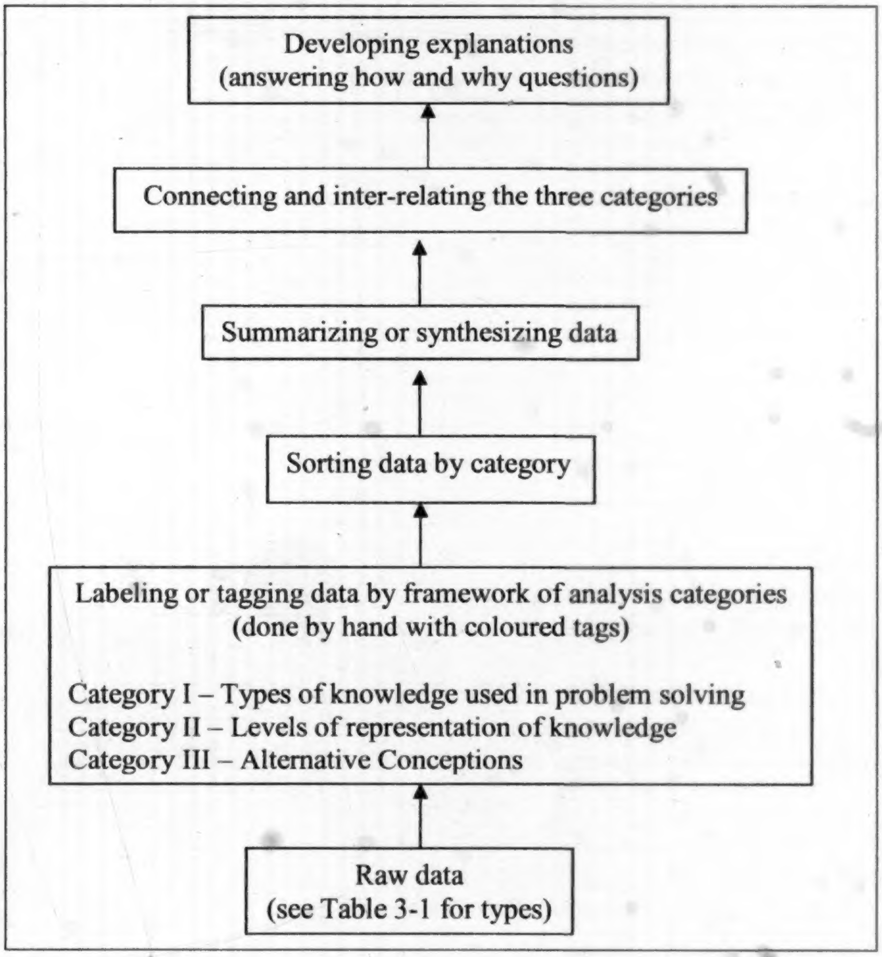
Qualitative research attempts to interpret phenomena in their natural setting by exploring the meaning-making associated with the phenomena to develop an in-depth understanding (Denzin & Lincoln, 1994). The researcher is a *bricoleur*, like a quilt or film maker, weaving together the complex aspects of the phenomena (Denzin & Lincoln, 2005). Multiple methods, or triangulation, are used to get in-depth understanding of phenomena to add rigour, breadth, and depth to the study, and is an alternative to validation (Denzin & Lincoln, 1994). The methodological '*bricoleur*', according to Denzin & Lincoln (2005), is a way of executing varied tasks such as self-reflection and interviewing, and uses various interpretive paradigms. They acknowledge that different paradigms are not easily synthesized, as "overarching philosophical systems have different ontologies, epistemologies, and methodologies" with their own world views (p. 6). A *bricoleur* works with contending and overlapping paradigms while being aware that research is not immune from personal histories and identities but is an interactive process affected by the researcher's history, gender, class, and ethnic identity (Denzin & Lincoln, 1994). Issues of reliability and validity could be addressed in relation to the quantitative data collected during development and use of the diagnostic tool, whereas the criteria of authenticity and trustworthiness could be used to evaluate the qualitative data (Guba & Lincoln, 2005).

Qualitative research in this inquiry was useful for the in-depth study of a limited number of samples with which I conducted comparisons and analysis. This provided understanding and description of students' personal experiences of phenomena (i.e., the "emic" or insider's viewpoint) through which the words and categories of students lend themselves to exploring how and why phenomena occurred (Johnson & Onwuegbuzie, 2004). The product of the research, a *bricolage*, represented a combination of practices using a variety of tools to find a solution to a problem in concrete ways using understandings and interpretations (Denzin & Lincoln, 1994). Generalizability, although perhaps statistically meaningful, would have had no applicability from such a small number of samples (i.e. 19 students); however, qualitative data can help avoid such ambiguity (Guba & Lincoln, 1994) and important aspects of a case could be used to demonstrate vividly a phenomenon to the readers of a report (Johnson & Onwuegbuzie, 2004).

Guba and Lincoln (1989) asserted that the criteria of credibility would be meaningful when assessing qualitative research. They described it as a parallel to internal validity and required "establishing a match between the constructed realities of respondents (or stakeholders) and those realities represented by the evaluator … (p. 237). The techniques to establish credibility used in this study included prolonged engagement during interviews, extensive observation, refining of the research question as the study progressed, and member checks with the teachers.

A number of different ways have been suggested to validate data in mixed methods research. Lewis and Ritchie (2003) identified two forms of triangulation: *methods triangulation* in which data that is generated by different modes (e.g., qualitative and quantitative) is compared, and *triangulation of sources* in which data from different qualitative methods (e.g., observations, interviews) are compared. The analysis of all forms of data collected in this study (see Figure 3-1) using the same categories of analysis was used to validate the data through source and method triangulation using the analytical hierarchy presented in Figure 3-6.

Figure 3-6. Analytical hierarchy used to analyze data in the research study.


Developing explanations
(answering how and why questions)
Connecting and inter-relating the three categories
Summarizing or synthesizing data
Sorting data by category
Labeling or tagging data by framework of analysis categories
(done by hand with coloured tags)
Category I – Types of knowledge used in problem solving
Category II – Levels of representation of knowledge
Category III – Alternative Conceptions
Raw data
(see Table 3-1 for types)

CHAPTER IV

DATA ANALYSIS AND DISCUSSION

Introduction

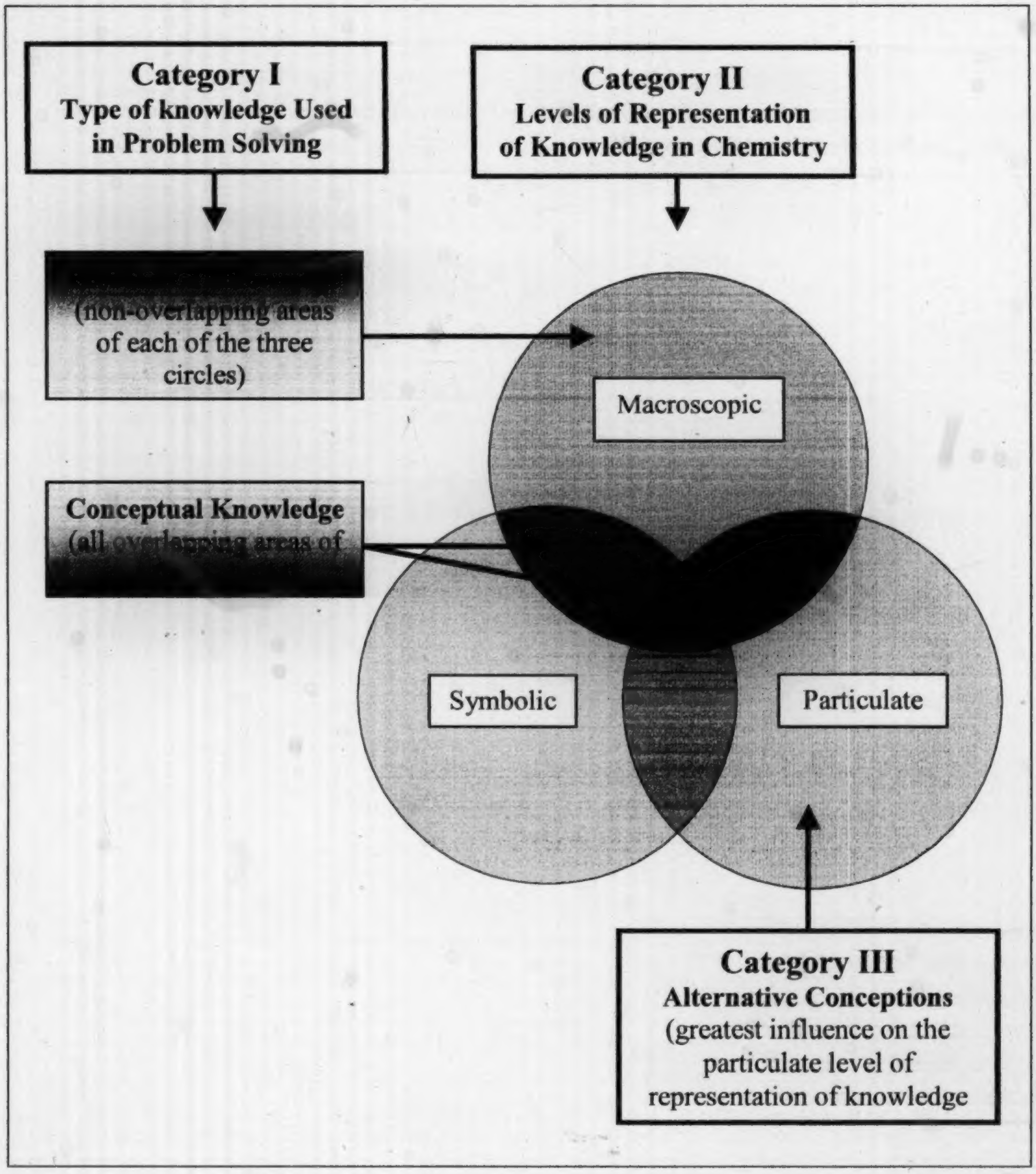
This chapter reports on the analysis of the qualitative and quantitative data from the pilot study and the main research study. The framework of analysis used for this data was comprised of the following three categories:

I. Types of knowledge used in problem solving
II. Levels of representation of knowledge in chemistry
III. Alternative conceptions

In this section, the data from the diagnostic instrument, student and teacher interviews, classroom observations, textbook analysis, and student and teacher notes will be presented for each of the three categories. The inter-relationship among the three categories will be discussed in Chapter V.

For category I, student use of procedural and conceptual knowledge when solving problems is discussed. These two types of knowledge are represented in Figure 4-1 as the non-overlapping sections of the three circles for procedural knowledge, and the overlapping sections of the three circles for conceptual knowledge. The three levels of representation of knowledge in chemistry in Category II are represented by the three circles labeled macroscopic, symbolic and particulate. Alternative conceptions in Category III were predominantly related to the particulate level of representation of knowledge because of the difficulty that students experienced with the abstract nature of atoms, molecules, ions and subatomic particles.

Figure 4-1. Relationship among the three categories used for the framework of analysis in this study


Category I
Type of knowledge Used in Problem Solving
Category II
Levels of Representation of Knowledge in Chemistry
(non-overlapping areas of each of the three circles)
Macroscopic
Conceptual Knowledge
(all overlapping areas of
Symbolic
Particulate
Category III
Alternative Conceptions
(greatest influence on the particulate level of representation of knowledge

Category I: Types of knowledge Used in Problem Solving

Overview of Category I Analysis

Students preferred to approach problem-solving with procedural knowledge. They generally scored higher on procedural knowledge questions in the main study diagnostic instrument, although there were a few exceptions. Students used decision routines involving memorized formulas and procedures to successfully solve both quantitative and qualitative problems. For routine problems that were familiar to them, a working-forwards problem-solving strategy was employed. However, for non-routine cells, students could not transfer their decision routines to novel problems because of limited conceptual knowledge of the underlying chemistry concepts.

Learning is defined as "the acquisition, retention, and use of large bodies of meaningful information …" (Ausubel, 2000, p. 67). Problem solving involves the use of both meaningful information and critical thinking in order to select an appropriate strategy that is based on the specific context needed to successfully solve a problem (Pushkin, 2007). For numerical problems in chemistry, Dahsah and Coll (2007) proposed that successful problem solving was related to a student's conceptual knowledge and involved the acquisition of a diverse knowledge base with exposure to a wide variety of concepts and problem contexts. Thus for a quantitative question, knowing the strategy to solve a problem may be procedural knowledge, such as the recall of a mathematical formula. However, recognizing the context in which to apply a specific strategy would be conceptual knowledge.

Procedural v Conceptual Knowledge

The overall results of the 10 two-tiered questions in the main study diagnostic instrument were that 71.9% of students correctly answered questions based on procedural knowledge (tier 1), and 61.1% of students were able to answer questions based on conceptual knowledge (tier 2) (see Table 4-1). These results were consistent with those conducted by Nakhleh (1993), Pickering (1990) and Sawrey (1990), in whose studies more that 60% of the students could solve procedural (algorithmic) problems, while less than 50% could solve conceptual problems about the same topics. Since relatively homogenous results were obtained across all the classes participating in the study with regard to class averages (i.e. 66-71%) and number of students within each range of scores (i.e. low: 40-59%, middle: 60-79% and high: 80-100%), the data was aggregated for analysis.

Table 4-1. Aggregated results of the main study diagnostic instrument. Data reported as percentage of students selecting the correct answer (n=87).

	Type of Knowledge		
Question	Procedural (tier 1)	Conceptual (tier 2)	Both
1	96.5	49.4	48.3
2*	49.2	51.6	31.0
3*	71.2	76.9	58.6
4	81.6	50.5	46.0
5	87.4	63.1	58.6
6	70.1	65.5	49.4
7*	61.9	67.7	44.8
8*	55.1	68.9	37.9
9	75.8	51.6	40.2
10	70.1	64.3	50.6
total	71.9	61.0	46.5

Note: see Appendix C for the main study diagnostic instrument. Questions with higher scores on conceptual knowledge (tier 2) than procedural knowledge (tier 1) are indicated by an asterisk.

Heyworth (1999) concluded that students sometimes solve algorithmic problems by applying formulas without necessarily learning the underlying scientific concepts. He defined algorithmic problems as those that required the application and manipulation of certain mathematics and science formulas. In this study, students were found to use procedures in an algorithm-like manner in order to solve non-mathematical problems. A specific framework or procedure used to organize information around a theme has been called a decision routine (Sweller, 2006), or a schema (Bröder & Schiffer, 2006; Newell & Simon, 1972; Mayer, 2008). In his study of expert (university professors) and novice (undergraduate students) problem solvers, Sweller (2006) described a decision routine as a procedure that integrates multiple elements of information or skills into a single element to inform what actions should be taken in specific contexts. For an expert, a procedure to solve a problem may have a single element, with an element defined as "anything that needs to be understood or learned". By contrast, a novice may require numerous steps to solve the same problem. A decision routine serves to automate the problem-solving process by activating a number of steps as a single element rather than processing them as individual elements. This in turn serves to decrease the working memory required to solve the problem. However, novices may have a limited conceptual knowledge base, which is required to identify the specific context in which a decision routine can be applied. The term decision routine in this study is applied to both mathematical manipulations and the process of solving qualitative problems using a step-like method comparable to the application of a formula in a quantitative problem. The notion of a novice to expert continuum (Bransford et al., 2000) is appropriate with the teachers representing more experienced problem solvers than their students.

Questions with Higher Conceptual Knowledge Scores

On four questions in the main study diagnostic instrument, students scored higher on the conceptual knowledge questions in tier 2 (see Table 4-1) than on the procedural knowledge questions (tier 1). For conceptual knowledge question 2-2 (see Appendix C), several of the students interviewed misread or interpreted the alternatives when selecting a correct response. For example, for alternative A – a half-reaction with a negative reduction potential will be nonspontaneous, Fran misread it to mean that the net cell potential was negative in nonspontaneous reactions.

[Interviewer] "Do you mean that the half-cell reaction is nonspontaneous or that the overall reaction is nonspontaneous?"

[Fran] "The overall reaction because you need two half cells for it to work. It can't work if there is only one reaction"

For alternative B – cell potentials are determined by adding the reduction potential from the standard electrode potential table, Colin explained, "I just add the potentials from the two half cells," but he did not account for changing the sign when he wrote his oxidation equation prior to his addition when calculating the net cell potential.

Students may have scored higher on conceptual knowledge question 3-2 (see Appendix C) because similar questions were practiced in class which is in agreement with the research by Sweller (2006). Three questions assigned from their textbook, four questions on worksheets, and one question on the unit test were similar to this question on the main study diagnostic instrument.

For procedural knowledge question 7-1 (see Appendix C), 95.1% of students selected the chemical species with the correct numerical value for the net cell potential. However, 33.2% of these students chose alternative D, species with a positive net cell potential, whereas 61.9% of students selected the species with the correct value and the correct negative sign. Five of the eight students interviewed who selected alternative D spontaneously identified this error and made the correct choice when discussing their diagnostic instrument results.

Although question 8-2 (see Appendix C) was classified as conceptual knowledge, 15 of the 19 students interviewed about this question had memorized a formula without meaningful learning of the underlying chemical concepts. As Liam explained, "I just plug the numbers into a formula. As long as I can remember the formula I can get the question right but I can't always remember which one I am supposed to use." For question 8-1 (see Appendix C), 28.6% of students did not recognize a reduction half-reaction, a concept which I had considered procedural knowledge because it could be answered by applying a definition or comparing the half-reactions to those in the redox table used in class.

For the remaining six questions, students scored higher on the tier 1 procedural knowledge questions than the tier 2 conceptual knowledge question (see Table 4-1).

Quantitative Decision Routines

Three questions in the pilot study diagnostic instrument and one question in the main study diagnostic instrument required a stoichiometry calculation. Stoichiometry questions and their analysis are presented in Figures 4-2, 4-3, and 4-4 and Tables 4-2, 4-3, and 4-4.

Question 7 in the pilot study diagnostic instrument involved an electrolytic cell calculation to determine the time required to deposit a particular mass of copper metal given the current supplied to the cell (see Figure 4-2). A student solved a similar problem on a worksheet assigned in class by using the following three steps:

1. calculate the number of moles of copper deposited using the formula, $n = \frac{m}{M}$

   (n = amount in moles, m = mass, M = molar mass)
2. determine the mole ratio between electrons and copper using a half-reaction

   equation, $Cu^{2+}_{(aq)} + 2\ e^{-} \rightarrow Cu_{(s)}$ (2 to 1 ratio)
3. calculate the time required by rearranging the formula, $n = \frac{It}{F}$

   (n = moles, I = current in amperes, t = time in seconds, F = Faraday's constant)

Seventy percent of students who wrote the pilot study diagnostic instrument could not start question 7 (see Table 4-2) because their problem-solving strategy seemed to be to apply a quantitative decision routine. Indeed 14 of the 23 students stated that they could not remember the formula. Thirty percent of students attempted to write a formula but it was incorrect; only 9% of these responses indicated partial learning and none of the responses indicated meaningful learning (see Table 3-6). Sidney explained how he approached this question. “I memorize and then manipulate the formula when doing calculations, but I forgot the formula to use”. He was then asked, “Is there another way that you can approach this question if you cannot remember the formula?” He replied, “I don’t think so. I just memorize the formula.”

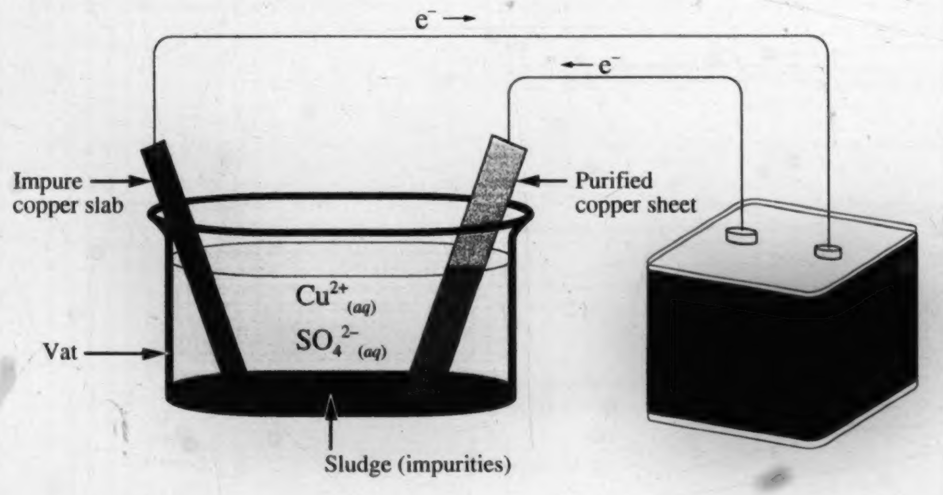
Sidney recognized that a calculation was required and the decision routine that he typically followed with this type of problem was the application of a formula. Indeed, he identified this preference during the pre-interview activity. The memorization of a formula is a decision routine that requires procedural knowledge. None of the students interviewed seemed to have the conceptual knowledge needed to solve the question without a memorized formula because they did not appear to have learned the relationship between the variables in the equation and, as Sydney explained above, could not approach the question using another process. Furthermore, an examination of their problem-solving process revealed that they did not remember that in a problem that involved two different substances, a mole ratio was required to convert from one substance to another, in this case from moles of electrons to moles of copper.

Figure 4-2. Procedural knowledge question 7 in the pilot study diagnostic instrument followed by an open response question to obtain information about student problem-solving strategies

---

Use the following information to answer the next question.

Copper can be refined (purified) using an apparatus like the one shown below, which is a small-scale version of an industrial apparatus.


e^- →
← e^-
Impure copper slab
Purified copper sheet
$Cu^{2+}_{(aq)}$
$SO_4^{2-}{}_{(aq)}$
Vat
Sludge (impurities)

Numerical Response

7. If the direct current power supply produces a steady 3.50 A current, then the time required to deposit 0.100 g of purified copper is __________ s.

The reason for your choice in the question above is

____

____

Table 4-2. Analysis of numerical response answers to question 7 in the pilot study diagnostic instrument (n=23)

Student Answer	Number of Students	Percentage
86.8 *	0	0
35	4	17.4
0.35	1	4.3
0.00	1	4.3
43.3	1	4.3
No response	16	69.6

Note: the correct response is indicated by an asterisk.

Question 8 in the pilot study diagnostic instrument involved a redox titration calculation using the provided data to determine the concentration of iron(II) ions in a sample of a solution (see Figure 4-3). During classroom observations, Ms. Maloney demonstrated how to solve a similar question during a lesson by using the following four steps:

1. Calculate that average volume of the titrant ($KMnO_{4(aq)}$) used in the problem.
2. Calculate the moles of titrant used with the formula, $n = Cv$.

   (n = moles, C = concentration, v = volume)
3. Write the net ionic equation for the titration to determine the mole ratio required to convert moles of titrant to moles of sample. The reaction for the titration in question 8 is represented by the following equation.

   $MnO_4^-{}_{(aq)} + 8\ H^+{}_{(aq)} + 5\ Fe^{2+}{}_{(aq)} \rightarrow 5\ Fe^{3+}{}_{(aq)} + Mn^{2+}{}_{(aq)} + 4\ H_2O_{(l)}$
4. Calculate the concentration of iron(II) ions in the sample by using the formula, $C = \frac{n}{v}$.

Thirty-two percent of students wrote one or more formulas implying meaningful or partial learning (see Table 3-6) on the open-response section of this question. However, 82% of students did not know how to begin the question, and either gave no response or indicated that they could not remember the formula. The remaining 18% of students could write some formulas but either did not attempt to write a balanced chemical equation or wrote it incorrectly, and so did not have the mole ratio needed to complete the calculation. Joanna successfully solved the problem and explained how she approached it. "I used formulas to solve the problem. I like the mathematical nature of this type of problem because it is easy to memorize a formula and get the question right".

None of the students in the pilot study successfully answered question 7 (see Table 4-2), whereas 44% of students correctly answered question 8 (see Table 4-3). When Pam was asked, "Can you explain to me why you found question 8 easier than question 7?" she replied, "We already did titration questions in grade 11 so I could remember the formula better. The other one was a new formula that we learned this year so I have a harder time remembering it". This supports the findings of Niaz and Chacon (2003) that types of problems requiring conceptual knowledge when introduced may eventually only require procedural knowledge with sufficient practice.

Figure 4-3. Procedural knowledge question 8 in the pilot study diagnostic instrument followed by an open response question to obtain information about student problem-solving strategies

---

Use the following information to answer the next question.

A student used an acidified 6.31×10^{-2} mol/L $KMnO_{4(aq)}$ solution to titrate 25.0 mL samples of $Fe^{2+}{}_{(aq)}$ solution of unknown concentration. In the reaction, the $Fe^{2+}{}_{(aq)}$ ion was oxidized to the $Fe^{3+}{}_{(aq)}$ ion. The student completed five trials and summarized the data in a table.

Trial Number	**1**	**2**	**3**	**4**	**5**
Final Buret Reading (mL)	17.55	35.65	26.40	42.65	16.85
Initial Buret Reading (mL)	0.30	17.55	10.05	26.40	0.55
Final Colour	purple	purple	pink	pink	pink

8. According to the student's data, the concentration of $Fe^{2+}{}_{(aq)}$ is

A. 0.206 mol/L
B. 0.213 mol/L
C. 0.218 mol/L
D. 0.223 mol/L

The reason for your choice in the question above is

____

____

____

Table 4-3. Analysis of numerical response answers to question 8 in the pilot study diagnostic instrument

Question 8	Number of Students	Percentage
A*	10	43.5
B	1	4.3
C	6	26.1
D	2	8.7
No response	4	17.4

Note: the correct answer is indicated with an asterisk.

The decision routine to answer both questions 7 and 8 that was used by all three teachers who validated the pilot study diagnostic instrument involved completing the calculation in a single step that included both formulas and a mole ratio obtained by looking at the redox table, but without writing an equation. When talking about how he presented a problem like this to his students, Mr. Weber pointed out, "I don't combine steps like I have done here when doing problems on the board because the short cuts would confuse students that have trouble with math". When asked, "Do you show students more than one method to solve a question like this?" two of the three teachers indicated that they only used formulas. Mr. Smyth said "I walk them through the dimensional analysis method shown in the textbook (substituting values so that the units can be cancelled) but I find that students think it is too much work and use formulas because it is easier to memorize how to do it. However, when we did a lab activity during a field trip at [a local community college] the instructor completed all the calculations with dimensional analysis. When they came back, a few students seemed a little more open to the other method because they might need to use it next year. It surprised me that it took a different context to finally increase the value of a method that requires less memorization." This supports the findings of Nieswandt (2007) that motivational factors can be more important than cognitive factors in promoting conceptual development in students.

Question 8 (see Figure 4-4) in the main study diagnostic test included a stoichiometry problem in the second tier. A sample problem in the student textbook (*Nelson Chemistry*, 1993, p. 418) solved a similar problem that involved copper using the following three steps.

1. Calculate the moles of electrons using the formula, $n = \frac{It}{F}$.
2. Convert moles of electrons to moles of metal using the half-reaction equation.
3. Calculate the mass of metal by using the formula, $n = mM$.

For question 8-1, 55.1% of students were able to identify the reduction half reaction that applied to a given equation, and for question 8-2 68.9% of students were successful with the stoichiometry calculation (see Table 4-4). Individually, both of these questions could be considered procedural knowledge.

For question 8-1, 17 of 19 students memorized the vocabulary needed to answer this question by using acronyms. Olivia explained, "GER means gains electrons reduced, and GERC means gains electrons reduced at cathode. That is how I remember how to answer questions like this. So if electrons are gained, then they are reactants".

For question 8-2, seven students wrote the equation $m = \frac{ItM}{FV}$, (m = mass, I = current, M = molar mass, F = Faraday's constant, V = valence electrons) and substituted the numbers. However, the data from Ben, Patrick and Fran provides evidence that students may be approaching quantitative problems with procedural knowledge. For example, Ben explained the V in the formula that he wrote.

> The V is the valence of your cathode, so it is the reduction reaction at the cathode. So, how many electrons it takes to cause one of the ions to turn into a solid refers to the valence of the ion undergoing redox, in this case aluminum ions, information that is obtained from the reduction half-reaction equation. I wasn't sure how many electrons were needed on my cathode. I just went through and did the numbers but I am not sure if I got the correct answer.

Although Ben selected the correct half-reaction equation for the reduction occurring in the reaction in question 8-1 and the correct equation for the calculation in question 8-2, he did not seem to transfer this knowledge between the two tiers of this question. He was next asked, "What is the relationship between the amount of aluminum and the amount of electrons?" Ben responded, "If the aluminum has a charge of plus 3, it would take three negative electrons to cause that one ion to turn into a solid. The solid is usually neutral. It takes three electrons for every one of aluminum." After a pause he continued, "Oh, there is the number I was missing for the calculation."

Patrick also provided the mathematical equation, $m = \frac{ItM}{FV}$ for question 8-2 and explained, [Patrick] "*V* is the electrons. This is what I always screw up on. Would it be 4 electrons?"

[Interviewer] "Why do you think it might be 4 electrons?"

[Patrick] "I am looking at the number of moles that are next to aluminum" (2 Al_2O_3 – the prescript multiplied by the subscript for aluminum).

These findings were consistent with those reported by BouJaoude and Barakat (2000) that some students did not understand the significance of the coefficients in a chemical equation. Fran applied her decision routine even more rigidly when she attempted calculations and explained how she converted from moles of electrons to moles of the metal.

[Fran] "I know there are three electrons so I divided by 3".

[Interviewer] "Why did you divide by 3?"

[Fran] "Because I know when I was writing our unit test I couldn't remember whether I had to divide or multiply. I picked divide and I got it right but I didn't know why. I think because the first time I multiplied it and then I did another question that was like that and I didn't have the option for when you multiply (as a choice in the multiple-choice alternatives) so I divided it and got the answer so I went back and changed it. So I know you had to do something with the three electrons. But then I just figure you divide so I have been doing that. For some reason, if you know the number of electrons then you multiply and if you are doing it you divide. So I just sort of memorized it, but I don't know why."

Figure 4-4. Two-tiered question 8 in the main study diagnostic instrument used to obtain information about student problem-solving strategies for stoichiometry problems

---

Use the following information to answer the next two questions.

An electrolytic cell is used to produce molten aluminum from molten aluminum oxide, as represented by the simplified equation below.

$$2\,Al_2O_{3(l)} \rightarrow 4\,Al_{(l)} + 3\,O_{2(g)}$$

8-1. Which of the following equations represents the reduction half-reaction when molten aluminum oxide undergoes electrolysis?

A. $2\,O^{2-}{}_{(l)} + 4\,e^- \rightarrow O_{2(g)}$

B. $2\,O^{2-}{}_{(l)} \rightarrow O_{2(g)} + 4\,e^-$

C. $Al^{3+}{}_{(l)} \rightarrow Al_{(l)} + 3\,e^-$

D. $Al^{3+}{}_{(l)} + 3\,e^- \rightarrow Al_{(l)}$

8-2. If 50 000 A were applied to the electrolytic cell for 5.00 h, then the mass of aluminium produced would be

A. 9.33×10^3 g

B. 8.39×10^4 g

C. 2.52×10^5 g

D. 7.55×10^5 g

Table 4-4. Cross-tabulation analysis of student answers to questions 8-1 and 8-2 in the main study diagnostic instrument. Data reported as percentage of students selecting the correct answer (n=87).

	Procedural Knowledge (8-1)						
		A	B	C	*D	total	Alternative Conception
Conceptual Knowledge (8-2)	A	0	0	1.1	2.3	3.4%	n_{e^-}
	[redacted]	[redacted]	[redacted]	[redacted]	37.9	[redacted]	
	C	3.4	2.3	2.3	13.8	21.8%	$n_{e^-} \times \frac{1}{1} \times M$
	D	1.1	2.3	1.1	1.1	5.6%	$n_{e^-} \times \frac{3}{1} \times M$
	total	16.0%	18.4%	10.2%	55.1%		

Note: n = moles; M = molar mass

The decision routine for a stoichiometry calculation used by Ben, Patrick and Fran discussed above involved the application of a formula but they did not seem to have the conceptual knowledge needed to relate the procedural knowledge about reduction and the decision routine for stoichiometry calculations. When the relationship between the two pieces of information was made explicit, students could proceed successfully. Mr. Smyth offered this explanation, "Students depend on me to look things up and do the calculations. They are very passive learners. Most students are content to follow along but not participate in the activity, therefore at test time they haven't actually done all the steps and are unsure of the calculation method. I have to keep telling them that they have to think through the steps – look things up, remember the formulas - not just watch me do it. I do have a number of students who are always ready with the numbers that they have looked up but I try to ask specific students for the information so that they are more likely to get involved with the discussion. It means that there is more wait time while they dig out their data books and look things up but once they get started they seem to be more likely to ask questions or make comments so the time is well spent for some of them". Mr. Weber agreed and added, "This is particularly true for demonstrations where many students want to watch and be entertained rather than working through the possible reasons for the process they are seeing and especially if it involves concepts from more than one unit". This was reinforced by Douglas during his interview in the pilot study when he expressed his frustration with chemistry. "I find chemistry really difficult because I do not understand it and need to do things in order. Homework is always done the same way as the stuff we did in class. The textbook questions are also in the same order as the stuff we did in class too so I can figure out what section I should look in for examples. On tests, there is no pattern so I can't figure it out." Douglas can apply a decision routine but did not seem to have the conceptual knowledge needed to relate a decision routine to a specific problem-solving context. Ian explains how he was able to increase his success in chemistry by increasing his intentionality. "I started to take a couple of notes and write down key elements of what I think is important which has actually helped me on the past couple of tests - by writing down things and actually doing the examples. And what I was doing with Mr. Smyth, was actually going over examples, not just reading over what the information was, but doing an equation and using the tables to find the things I needed."

When students were confronted with simple, predictable quantitative problems in this research, they resorted to memorized procedures or decision routines as described above, rather than meaningful learning of the concepts involved. Students who depended on procedures seemed to approach the task of solving problems with the intention to reproduce what they had memorized, rather than with the intention to find relations and seek to understand the underlying concepts required for the tasks.

Qualitative Decision Routines

The first instruction in the task-based interview was "Predict how a copper-zinc voltaic cell would be set up and how it would operate." Eighteen of the nineteen students who volunteered for these interviews wrote correct half-reaction equations using their redox table, assembled a voltaic cell with a solid copper electrode in a 0.10 mol/L copper(II) sulfate solution for the cathode half-cell, and a solid zinc electrode in a 0.10 mol/L zinc sulfate solution for the anode half-cell. They connected the electrodes with wires through a voltmeter and used either a salt bridge that contained a potassium nitrate solution or a porous cup to connect the electrolytes. The students identified that the path of the electrons would be from the anode, through the external wires and the voltmeter, to the cathode and that cations would move through the electrolyte towards the cathode and anions would move towards the anode. The voltaic cells that the students assembled are represented by Figures 4-5 and 4-6.

Figure 4-5. A representation of the copper-zinc voltaic cell using a porous cup that students assembled during the task-based interview

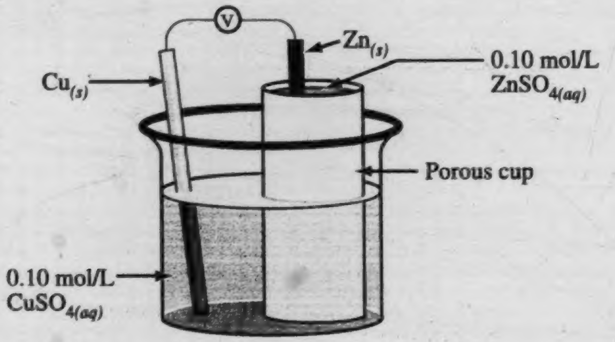
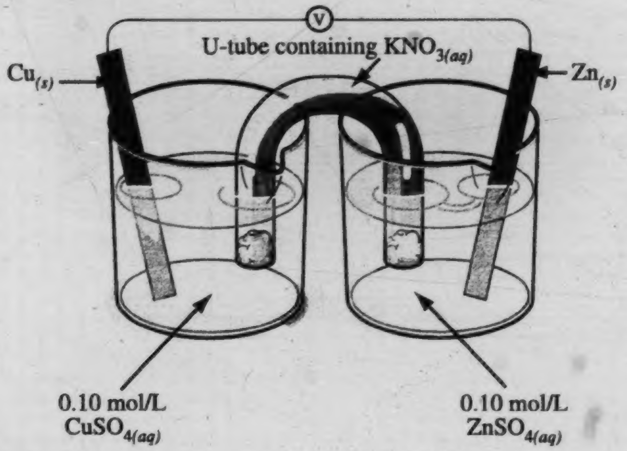

V
$Zn_{(s)}$
0.10 mol/L
$ZnSO_{4(aq)}$
$Cu_{(s)}$
Porous cup
0.10 mol/L
$CuSO_{4(aq)}$

Figure 4-6. A representation of the copper-zinc voltaic cell using a salt bridge that students assembled during the task-based interview


V
U-tube containing $KNO_{3(aq)}$
$Cu_{(s)}$
$Zn_{(s)}$
0.10 mol/L
$CuSO_{4(aq)}$
0.10 mol/L
$ZnSO_{4(aq)}$

Students had been introduced to a copper-zinc voltaic cell during their lessons. In one school, students had observed a demonstration of the operation of a copper-zinc cell in class and watched a computer animation of the particle movement in the cell. In the other school, students had set up a copper-zinc cell as part of a laboratory activity to measure the voltage produced by five different cells. Students' notes from both schools had half-reactions and a net ionic equation related to this cell and diagrams of the cell that included labels for electrodes, electrolytes, salt bridge, voltmeter, and movement of electrons through the wire, and cations and anions through the electrolytes. Generally, students could correctly answer the type of questions that are typically used on paper-and-pencil tests to assess their knowledge of the operation of voltaic cells. This information would lead us to predict that these students had conceptual knowledge of the operation of these cells. The processes that the students used to make predictions about their voltaic cell, however, seemed to be based on a memorized procedure and their explanations of how the voltaic cell operates revealed some surprising ideas.

Using the Redox Table

For the prediction during the interview involving the copper-zinc voltaic cell, students were asked, "How would it operate?" They readily used their redox tables to write a reduction half-reaction for copper and an oxidation half-reaction for zinc. While doing this, Colleen explains,

> The OA (oxidizing agent) is on the left hand side and the strongest one is found closest to the top of the chart and the substance undergoing reduction is at the cathode. The zinc solid is the SRA (strongest reducing agent) which is found by looking on the right hand side of the table and decreases in strength going up, and this is the anode side.

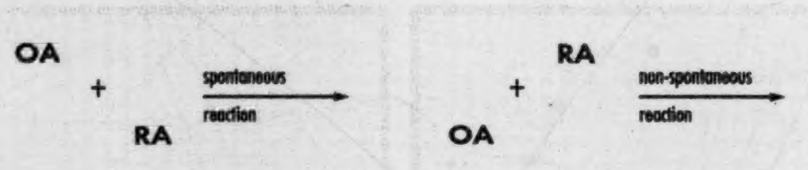
The reduction and oxidation half-reactions and overall equation that the students wrote for the prediction involving the copper-zinc voltaic cell are represented by the following equations.

$$\begin{array}{rl}
Cu^{2+}{}_{(aq)} + 2\,e^{-} \rightarrow Cu_{(s)} & E^{\circ} = +0.34\ \text{V} \\
Zn_{(s)} \rightarrow Zn^{2+}{}_{(aq)} + 2\,e^{-} & E^{\circ} = -0.76\ \text{V} \\
\hline
Cu^{2+}{}_{(aq)} + Zn_{(s)} \rightarrow Cu_{(s)} + Zn^{2+}{}_{(aq)} & E^{\circ}_{\text{cell}} = +1.10\ \text{V}
\end{array}$$

While writing these equations, 80% of students included the reduction potential values (i.e., $E°$) for the half-reactions and calculated the cell potential. Additionally, 60% of students applied labels to the half-reactions. For example, the first half-reaction shown above was variously labeled: cathode, SOA, reduction, or reduction/cathode. Student explanations about their label typically involved restating the definition of the term that they had used, for example "electrons are gained at the cathode" for the reduction/cathode label. Using these equations, some students were able to further predict that electrons from the oxidation of zinc solid would combine with copper(II) ions to produce solid copper which they would be able to observe at the cathode during the operation of the cell.

The information required to answer these questions may be procedural knowledge. Students seemed to have memorized a procedure, or developed a decision routine, that allowed them to successfully use a redox table to predict chemical reactions that would occur in a voltaic cell. The use of acronyms further allowed students to associate key vocabulary words with this procedure without conceptual knowledge of the underlying chemistry. For example, the acronyms "LEO" and "GER" represent "lose electrons oxidation" and "gain electrons reduction". The use of the redox spontaneity rule gave them another pattern that could be memorized. If the oxidizing agent in the left column of the table is above the reducing agent in the right column of the table, then the reaction is predicted to be spontaneous (see Figure 4-7).

Figure 4-7. A textbook diagram that illustrates the redox spontaneity rule and shows a pattern that can be memorized



From: [1]*Nelson Chemisry* (1993) (p. 355)
Note: OA represents the strongest oxidizing agent and RA represents the strongest reducing agent. Spontaneous and nonspontaneous refer to the type of reaction.

"OA above RA" for a spontaneous reaction is another example of an association that students used, often without understanding. For example, after Helen had correctly written her equations using the redox table, she was asked, "Why do copper(II) ions gain electrons before zinc ions which are located lower in the same column on the table?" She replied, "I don't know. It has a more positive charge in the electrode potential and that is what we are taught in class." Helen located her strongest oxidizing agent using the reduction potential values on the redox table. These are listed in numerical order from the most positive to the most negative (see Table 2-1). When Patrick was asked the same question, he restated his definitions, "Reduction is the gaining of electrons. An oxidizing agent causes oxidation so it has a greater tendency to cause the zinc to release its electrons" and then after a pause, "I guess I don't know why I am choosing the strongest".

---

[1] Jenkins et al. *Nelson Chemistry.*© 1993. Nelson Education Ltd. Reproduced by permission. www.cengage.com/permissions.

Students seemed to be unable to transfer the decision routine that was used to predict reactions using their redox table to a redox table that was comprised of different chemical species. Question 2-1 (see Figure 4-8) in the main study diagnostic instrument asked students to choose the strongest reducing agent on a redox table that was organized in the same way as the one used in class but with four unfamiliar reduction half-reactions. The strongest reducing agent was the species on left side of the table at the bottom, $V^{2+}{}_{(aq)}$. Fewer than 50% of students were able to answer this procedural knowledge question to which they could have applied the same definitions and acronyms to identify key characteristics of the redox table that they used in class with their familiar redox table (see Table 4-5).

Figure 4-8. Two-tiered question 2 in the main study diagnostic instrument

Use the following information to answer the next two questions.

Standard Electrode Potentials

$VO_2{}^+{}_{(aq)} + 2\,H^+{}_{(aq)} + e^- \rightarrow VO^{2+}{}_{(aq)} + H_2O_{(l)}$	$E° = +0.999$ V
$VO^{2+}{}_{(aq)} + 2\,H^+{}_{(aq)} + e^- \rightarrow V^{3+}{}_{(aq)} + H_2O_{(l)}$	$E° = +0.340$ V
$VO_2{}^+{}_{(aq)} + 4\,H^+{}_{(aq)} + 5\,e^- \rightarrow V_{(s)} + 2\,H_2O_{(l)}$	$E° = -0.250$ V
$V^{3+}{}_{(aq)} + e^- \rightarrow V^{2+}{}_{(aq)}$	$E° = -0.255$ V

2-1. Which of the following substances is the strongest reducing agent?

A. $V^{2+}{}_{(aq)}$
B. $V^{3+}{}_{(aq)}$
C. $VO_2{}^+{}_{(aq)}$
D. $VO^{2+}{}_{(aq)}$

2-2. Which of the following statements applies to the standard electrode potential table above?

A. A half-reaction with a negative reduction potential will be nonspontaneous.

B. Cell potentials are determined by adding the reduction potentials from the standard electrode potential table.

C. In a standard reduction potential table, reducing agents are listed in order of decreasing reactivity from the top of the table to the bottom of the table.

D. In a standard reduction potential table, species are listed in order of decreasing tendency to attract electrons from the top of the table to the bottom of the table.

Table 4-5. Cross-tabulation analysis of student responses to two-tiered question 2 in the main study diagnostic instrument. Data reported as percentage of students selecting the correct answer (n=87).

		Procedural Knowledge (2-1)					
		*A	B	C	D	total	Alternative Conception
Conceptual Knowledge (2-2)	A	3.4	4.6	8.0	3.4	19.4%	9c. Half-cell potentials are absolute in nature and can be used to predict the spontaneity of the half cells. (5)
	B	2.3	5.7	2.3	1.1	12.5%	14a. Cell potentials are derived by adding individual reduction potentials.
	C	11.4	3.4	1.1	0	15.9%	8b. Standard reduction potential tables list metals in order of decreasing reactivity from the top down. (2)
	[redacted]	31.0	[redacted]	[redacted]	[redacted]	[redacted]	
	total	49.2%	28.6%	13.7%	9.1%		

(2) Garnett & Treagust, 1992b; (5) Ozkaya, 2002.

In question 3 in the main study diagnostic instrument, students needed to apply definitions to answer 3-1, and for question 3-2 they needed to know the spontaneity rule (see Figure 4-7) and how the redox table was set up (see Figure 4-9). If they knew the spontaneity rule, and recognized that the positive ions on the left side were the oxidizing agents because the oxidation number was decreasing, then they could order the chemicals from the strongest to weakest oxidizing agent. For the two spontaneous reactions, the oxidizing agent was above the reducing agent, therefore, U was above La, and Y was above La. For the nonspontaneous reaction the oxidizing agent was below the reducing agent, so Y was below U. Thus the correct order would be found in alternative B. Over 70%

of students could answer these two questions individually; however, only 60% of students could answer both of these questions correctly (see Table 4-6).

Figure 4-9. Two-tiered question 3 in the main study diagnostic instrument.

Use the following information to answer the next two questions.

$$U^{3+}_{(aq)} + La_{(s)} \rightarrow La^{3+}_{(aq)} + U_{(s)}$$

$$Y^{3+}_{(aq)} + U_{(s)} \rightarrow \text{no reaction}$$

$$Y^{3+}_{(aq)} + La_{(s)} \rightarrow La^{3+}_{(aq)} + Y_{(s)}$$

3-1. Which of the following statements applies to the equations above?

A. The oxidizing agent loses electrons.
B. The reducing agent undergoes reduction.
C. The oxidation number increases in the species undergoing reduction.
D. Electrons are transferred from the reducing agent to the oxidizing agent.

3-2. The oxidizing agents above, listed from strongest to weakest, are

A. $U_{(s)}$, $Y_{(s)}$, $La_{(s)}$
B. $U^{3+}_{(aq)}$, $Y^{3+}_{(aq)}$, $La^{3+}_{(aq)}$
C. $U^{3+}_{(aq)}$, $La^{3+}_{(aq)}$, $Y^{3+}_{(aq)}$
D. $Y^{3+}_{(aq)}$, $U^{3+}_{(aq)}$, $La^{3+}_{(aq)}$

Table 4-6. Cross-tabulation analysis of student responses to two-tiered question 3 in the main study diagnostic instrument. Data reported as percentage of students selecting the correct answer (n=87).

Conceptual Knowledge (3-2)	Procedural Knowledge (3-1)						
		A	B	C	*D	total	Alternative Conception
	A	1.1	0	1.1	4.6	6.8%	8b. Standard reduction potential tables list metals in order of decreasing reactivity from the top down. (2)
					58.6		
	C	1.1	1.1	3.4	3.4	9.0%	
	D	1.1	1.1	0	4.6	7.2%	
	total	12.5%	3.3%	12.5%	71.2%		

(2) Garnett & Treagust (1992b)

The decision routine that students used to predict a reaction using their redox table was similar to a method in their textbook (see Table 4-7). The method was referred to as the "five-step method" by Mr. Smyth and Mr. Weber. For example, a question from an electrochemistry unit test that was administered at one school was, "Use the five-step method to predict the most likely redox reaction if a potassium dichromate solution is added to an acidic tin(II) chloride solution." The decision routine used to answer this question can be memorized and applied without conceptual knowledge of why a species is a stronger oxidizing agent than another, or what is happening to the electrons during the reaction. Indeed, only 51.6% of students (see Table 4-5) could answer conceptual knowledge question 2-2 (see Figure 4-8) which was based on understanding how the redox table was set up whereas 76.9% of students (see Table 4-6) could answer questions that could be done by applying the five step method.

Table 4-7. Five-step method: A qualitative decision routine used to predict the products and spontaneity of reactions using the redox table

Step 1: List all entities present and classify each as a possible oxidizing agent, reducing agent, or both.

Step 2: Choose the strongest oxidizing agent as indicated in the table of redox half-reactions (highest species in the left column of the table), and write the reduction half-reaction equation.

Step 3: Choose the strongest reducing agent as indicated in the table of redox half-reactions (lowest species on the right column of the table), and write the oxidation half-reaction equation.

Step 4: Balance the number of electrons lost and gained in the half-reaction equations by multiplying one or both equations by a number. Then add the two balanced half-reaction equations to obtain a net ionic equation.

Step 5: Predict whether the net ionic equation represents a spontaneous or nonspontaneous redox reaction using the spontaneity rule (see Figure 4-7).

From: [1]*Nelson Chemistry* (1993), p. 362. Notes in brackets added by the author

Calculating Cell Potential

The cell potential is the difference between the electrical potential of the oxidation and reduction half-cells. It can be calculated using the formula, $E^\circ_{\text{cell}} = E^\circ_{\text{cathode}} - E^\circ_{\text{anode}}$ Calculating a difference mathematically requires a subtraction. The values that are substituted into the formula are the reduction potential values from the redox table. When students wrote the half-reactions to predict the reaction that they expected to occur in their voltaic cell, they typically included an E° value beside the half-reaction. When writing the reduction potential beside the oxidation (anode) half-reaction, 50% of the students interviewed changed the mathematical sign on the number from a negative to a positive. The example in Table 4-8 represents the process used by a student on a worksheet that was assigned in class.

---

[1] Jenkins et al. *Nelson Chemistry.*© 1993. Nelson Education Ltd. Reproduced by permission. www.cengage.com/permissions.

Table 4-8. A student's calculation of cell potential on a worksheet assignment

For the following cells, write the cathode, anode, and net cell reaction equations and calculate the cell potential.

a) lead-copper standard cell

cathode	$Cu^{2+}_{(aq)} + 2\,e^- \rightarrow Cu_{(s)}$	$E° = +0.34$ V
anode	$Pb^{2+}_{(aq)} + 2\,e^- \rightarrow Pb_{(s)}$	$E° = -0.13$ V (flip sign)
cathode	$Cu^{2+}_{(aq)} + 2\,e^- \rightarrow Cu_{(s)}$	$E° = +0.34$ V
anode	$Pb_{(s)} \rightarrow Pb^{2+}_{(aq)} + 2\,e^-$	$E° = +0.13$ V
net	$Cu^{2+}_{(aq)} + Pb_{(s)} \rightarrow Cu_{(s)} + Pb^{2+}_{(aq)}$	$E°_{cell} = +0.47$ V

The method used to solve this problem was similar to a method presented in a Chemistry 30 textbook (*Addison-Wesley Chemistry*, 1993, p. 513), and in a video shown in class (Access, 1996). This method used the formula, $E°_{cell} = E°_{reduction} + E°_{oxidation}$, with the oxidation potential assigned the opposite sign to the reduction potential from the students' redox table and involving an addition rather than a subtraction. Some students were able to explain that the electrons needed to be balanced between the two equations and reversing the sign corresponded to reversing the reduction equation from the redox table to an oxidation equation. However, over 60% of students interviewed who used this method were unable to give a reason for "flipping the sign", but indicated that they always did it. Indeed when Ruth wrote the oxidation equation first, she still reversed the sign on the second equation, in this case the reduction equation explaining, "Because you are reading it from, because you change it. I am not sure why Mr. Clarke said to do that, but I just remember to always change the second one". The use of this decision routine without conceptual knowledge did not allow Ruth to recognize incorrect work because she assumed that if she followed a method, then a correct answer would be generated. Mr. Clarke reflected on his student's response, "Although this calculation is defined as finding the difference which is subtraction, I explained to my students when teaching this that by flipping the sign they might make fewer mathematical errors because they don't have to worry about subtracting a negative. I didn't anticipate that they would simply take the one step out of the context of the process and ignore the reason behind it. No wonder so many of them mix this up. I guess I forget that I know the context because I do this so often but they are doing it for the first time and I really need to remember that they are novices. Explaining it once is not the same as helping them to understand because they are not making the same connection that I am." This is consistent with the findings of Sanger and Greenebowe (1999), that the imprecise use of scientific vocabulary can be a source of alternative conceptions for students in chemistry.

Routine Voltaic Cells

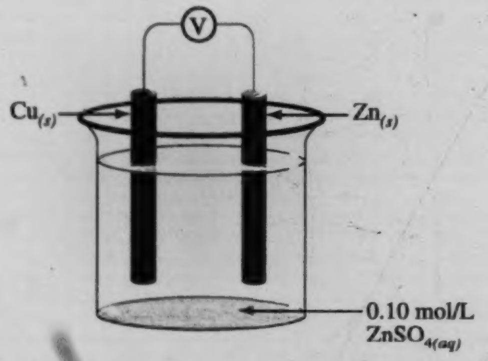
Students were proficient at setting up copper-zinc voltaic cells, but they did not have conceptual knowledge about the components needed for these cells. As Dan was assembling his voltaic cell, he was asked "Why did you place the strip of copper metal in the copper(II) solution rather than in the zinc solution?" he replied, "I don't know. That is the way it was in the textbook". Peggy wrote the equations and set up the voltaic cell without referring to the redox table. She was asked, "How did you decide which reaction you would write down and which materials you would use to build your voltaic cell?" Peggy explained, "The way that I was taught was that we always did reduction half reactions first, so I just assumed that copper was reduced because I have been doing so many of these equations in class." She was next asked, "Why did you place the strip of copper metal in the copper(II) solution rather than in the zinc solution?" and she said "I saw this set up in the textbook. I'm not sure why". Peggy's problem-solving approach was to reproduce what she had memorized rather than finding relations and understanding the task.

Students had been introduced to voltaic cells in grade 9 (Alberta Education, 2003) and their textbooks (e.g., *Science Focus 9*, 2002) had many diagrams that showed the components and uses of everyday batteries. The explanations and laboratory activities in the textbook; however, were all based on wet cells that contained two metal electrodes and an electrolyte. In the Chemistry 30 textbook, 54% of the voltaic cell diagrams showed two metals in ionic solutions (*Nelson Chemistry,* 1993). For the purposes of this study, I classified this to be the routine voltaic cell because it was the one with which the students were most familiar. Fifteen percent of students interviewed seemed to have developed a decision routine based on this routine cell. For example, Quinn found the two metal solids on the redox table and then wrote the one with the larger value for voltage first. This decision routine is successful for all voltaic cells that are routine – those that contain two metals and their ionic salts. But students must also be able to analyze the context of the problem or they will be unwilling or unable to change their problem-solving strategy for novel problems.

Probing Conceptual Knowledge – Non-routine Voltaic Cells

The decision routine that students followed to set up a copper-zinc voltaic cell was to write the half-reaction equations for the prediction, and then assemble the cell with each metal electrode in its ionic solution in separate half cells connected with a salt bridge or porous cup. In order to differentiate between procedural knowledge and conceptual knowledge, students were asked, "Can the voltaic cell be set up in one beaker using one electrolyte?" Students first made a prediction and then proceeded to set up the voltaic cell using two electrodes in one beaker with a single electrolyte. Eighteen of the nineteen students in the study selected the zinc nitrate solution as the electrolyte (see Figure 4-10).

Figure 4-10. A representation of a non-routine voltaic cell that students assembled during the task-based interview. This cell had two electrodes in one electrolyte and will not operate because no reduction reaction can occur; an oxidizing agent is not present.



After observing that no voltage was produced in the cell that they had assembled, students were asked, "Why do you think this cell does not operate?" These interviews about this non-routine problem identified two areas of conceptual difficulty for the students: the salt bridge and the function of the oxidizing agent.

The Salt Bridge

Ten of the nineteen students interviewed believed that it was the absence of the salt bridge that prevented the cell from operating. The salt bridge is used in a routine copper-zinc voltaic cell when the cell is set up as two physically separated half cells. For the routine cell, students were able to explain that ions passed through the salt bridge in order to maintain electrical neutrality in the cell. Liam had memorized "a attracts a" and "c attracts c" which he explained means, "the anions move towards the anode and cations move towards the cathode". However, they did not seem to have the conceptual knowledge to recognize that this was a function of the reactions that occur and not the physical presence of the salt bridge. For example, when Liam was asked, "Why is the anion attracted to the anode", he replied, "I don't really know. Memorizing that 'a attracts a' helps me to remember it but I guess I don't remember why it happens". After reading Liam's explanation, Mr. Clarke explained, "I do teach the ion movement in the context of the functioning of the cell so I really thought they would get more than just a recall cue from the lesson. Since they are not getting why this is happening, I will have them come up with a way to figure it out themselves and make up their own acronym. I worry about the amount of time it will take to do this and the possibility that they will come up with some way that isn't true, like a combination of mistakes or misconceptions that still gets to a correct answer." Mr. Smyth added, "Maybe they shouldn't come up with this all on their own. If students suggest different ideas, perhaps we can guide them during a discussion to decide which ideas make the most sense. If they make this decision themselves, then they are more likely to remember the context of the discussion and then remember the important details, not just isolated bits of information without meaning like they are doing now."

The Function of the Oxidizing Agent

The cathode half-reaction represents the reduction of the strongest oxidizing agent present in the cell. The source of electrons for this reduction is the oxidation reaction that occurs at the anode. The two reactions occur simultaneously. Students had used procedural knowledge to write the reduction half-reaction as $Cu^{2+}_{(aq)} + 2\,e^{-} \rightarrow Cu_{(s)}$ using the redox table, but they did not have the conceptual knowledge to recognize that the copper(II) ion was required for the redox reaction to occur. Indeed, only two of the nineteen students referred to the equations that they had previously written for the routine copper-zinc voltaic cell when attempting to discover why the non-routine voltaic cell was not producing a voltage when a zinc sulfate electrolyte was used.

A strategy used by novice problem solvers was described by Newell and Simon (1972). When faced with a novel situation in which they were unsure what action to take, novices would not have a decision routine available to use to attempt to solve the problem. Moves must be generated randomly and tested by using a "means-ends" strategy in which the current state of the process and the goal are compared until a solution is found or until no more strategies can be generated.

For novel problems, students proceeded using a means-ends problem-solving strategy by changing the cell set-up until a voltage was observed; this was the goal of the problem. The voltaic cell did operate when the copper and zinc electrodes were placed in a copper(II) sulfate solution, but the cell potential was lower than in the routine voltaic cell designs shown in Figures 4-5 and 4-6. After looking at her half-reaction equations, Olivia recognized that both zinc ions from the oxidation reaction and copper(II) ions from the electrolyte were present. She explained the lower voltage in her cell, "Both ions are there and there will be more repulsion. They are moving around and they can't move as fast because of the repulsion." Each student recorded an observation that a layer of solid copper was visibly forming on the zinc electrode while the cell operated. This was a spontaneous reaction between the solid zinc and the copper(II) ions in solution – the same reaction that was predicted for the routine voltaic cell, albeit physically separated in the two half-cells. None of the students identified, however, that a layer of solid metal might act as a barrier, and interfere with the operation of their cell by limiting the availability of solid zinc for oxidation. Although students used vocabulary, such as oxidizing and reducing agents, it was apparent that they lacked understanding of their function in the electrochemical cells that they were building.

Electrolytic Cells

To explore students' procedural and conceptual knowledge about electrolytic cells, they were invited to "Predict how a copper electroplating cell would be set up and how it would operate." When asked, "How do you think an electrolytic cell is different from a voltaic cell?" all students explained that in an electrolytic cell the reaction was nonspontaneous and a power source replaced the voltmeter. Additionally, over 75% of students stated that the value of the cell potential would be negative. The first step of the decision routine for voltaic cells involved using the redox table to predict the reactions that would occur. For electrolytic cells, only six of the nineteen students used this problem-solving strategy. Of those six students, only four were able to set up an electrolytic cell that plated copper onto the copper electrode (see Figure 4-11). Over 50% of the students chose both a solid copper and a solid zinc electrode to place in a copper(II) sulfate solution which created a spontaneous reaction (see Figure 4-12).

Figure 4-11. A representation of an electrolytic cell design that students set up during the task-based interview that could be used to electroplate solid copper onto a copper cathode in the cell

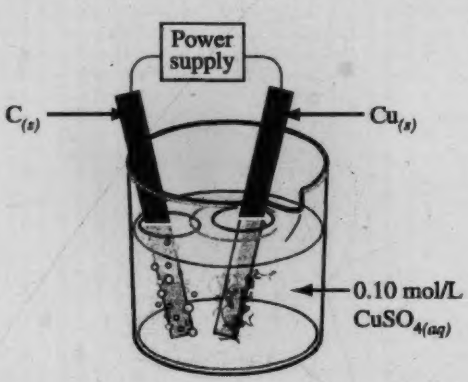
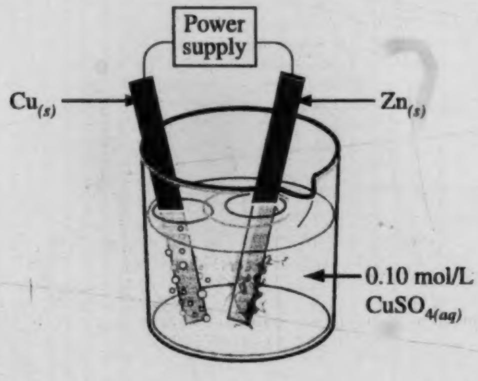


Figure 4-12. A representation of the most common electrolytic cell that was set up by students during the task-based interview. This cell contained the same electrodes as those used in the voltaic cell previously set up and resulted in a spontaneous reaction.



As described above, when copper plating was observed on the zinc electrode even before the power source was turned on, students did not seem to recognize that the same spontaneous reaction that had occurred in their voltaic cell was also occurring in their electrolytic cell, even though they had correctly identified the differences between the two types of cells. Conor observed, “There must be carbon forming on the electrode”. When asked to explain this he said, “It is coming from the carbon in the inert electrode”. The reactions that did occur in this electrolytic cell are represented by the following equations.

$$\begin{array}{ll}
\mathrm{Cu}^{2+}{}_{(aq)} + 2\,\mathrm{e}^{-} \rightarrow \mathrm{Cu}_{(s)} & E^{\circ} = +0.34\ \mathrm{V} \\
\mathrm{H_2O}_{(l)} \rightarrow \mathrm{O}_{2(g)} + 4\,\mathrm{H}^{+}{}_{(aq)} + 4\,\mathrm{e}^{-} & E^{\circ} = +1.23\ \mathrm{V} \\
\hline
2\,\mathrm{Cu}^{2+}{}_{(aq)} + \mathrm{H_2O}_{(l)} \rightarrow 2\,\mathrm{Cu}_{(s)} + \mathrm{O}_{2(g)} + 4\,\mathrm{H}^{+}{}_{(aq)} & E^{\circ}{}_{\mathrm{cell}} = -0.89\ \mathrm{V}
\end{array}$$

When equations were attempted using the redox table, the decision routine was different than that used for voltaic cells. For voltaic cells, 80% of students followed the five-step method: list the chemical species present, write the reduction half-reaction, write the oxidation half-reaction, balance the electrons and write the net equation, and decide whether or not the reaction is spontaneous (see Table 4-10). Ken wrote the oxidation half-reaction for water first and then the reduction half-reaction for copper. He then flipped the sign on the second half-reaction and explained, "I need a negative net potential for a nonspontaneous reaction and I want two negative signs". Ken knew that the cell potential in electrolytic cells is negative because "you can recognize a nonspontaneous reaction by the negative voltage value", and adjusted his numbers to obtain it. When asked to identify the cathode and anode in her electrolytic cell, Nancy found the two relevant reactions on the redox table and then ordered them for the calculation so that she would get the correct mathematical sign, "The cell potential must be negative because the reaction is spontaneous. I need the copper (half-reaction) to be negative too so that when I add them the answer will be negative". Both of these students had procedural knowledge, memorized facts related to electrolytic cells, but did not have conceptual knowledge about how these facts related to the chemistry of the cell.

When selecting the equipment he would use to set up his electrolytic cell, Liam explained, "I'm not sure if you need the zinc because the zinc will decay as the SRA so the carbon electrode would probably be an advantage because there won't be any loose zinc ions floating around in there that would get plated to the copper and dilute the mixture". He believed that solid zinc was needed as the strongest reducing agent; but after comparing the current state of his problem with the goal using the means-ends problem-solving strategy, he replaced the solid zinc with the inert electrode. He perceived that the more important goal of the solution to the problem was to obtain a pure copper plating, rather than designing an operating cell to accomplish the copper plating.

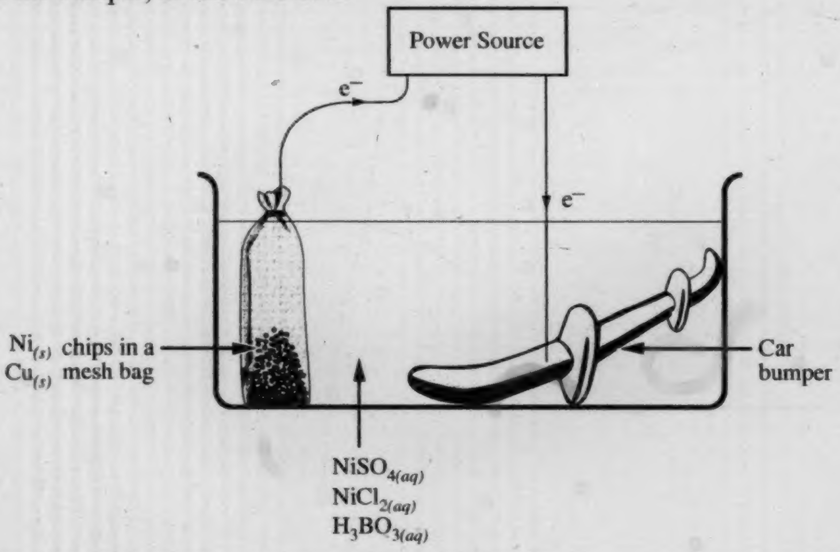
Even though all of the students interviewed could correctly define electrochemical terms and use them for voltaic cells, only 75.8% (see Table 4-9) of students could use this knowledge for an electrolytic cell in question 9-1 (see Figure 4-13). However, the alternative conception that the anode could be identified by its location in the cell was not held by the four students interviewed who selected alternative A in question 9-2. They interpreted information in the question, such as the direction of electron flow, to identify a location but did not relate it to one particular half-cell. For example, Colleen explained how she had identified the location of the anode in the diagram in this question, "I just looked at the electrons. Electrons go from the anode to the cathode, 'a to c' like the alphabet. Since the electron arrow is pointing to the left, then this one (the electrode on the left) has to be the anode". Although students do know facts about the anode – the site of oxidation, electrons travel from anode to cathode – only about 50% of students could interpret and answer the conceptual knowledge question. This question was conceptual knowledge because it did not involve identification of a definition presented in class lessons or the textbook, but involved knowledge of the meaning of the definition.

Figure 4-13. Two-tiered question 9 in the main study diagnostic instrument

---

Use the following information to answer the next two questions.

In order to refinish a car bumper, the first step is to clean the bumper and repair any damaged areas. The second step is the electroplating of nickel on the bumper, as shown below.



9-1. *The plating of the car bumper will take place at the _i_ where _ii_ occurs.*

The statement above is completed by the information in row

Row	*i*	*ii*
A.	anode	oxidation
B.	anode	reduction
C.	cathode	oxidation
D.	cathode	reduction

9-2. The anode in the electrochemical cell above is

A. identified by its location in the cell
B. the species with the highest reduction potential
C. the metal with the least ability to attract electrons
D. the electrode with the highest concentration of electrons

Table 4-9. Cross-tabulation analysis of student responses to two-tiered question 9 in the main study diagnostic instrument. Data reported as percentage of students selecting the correct answer (n=87).

		Procedural Knowledge (9-1)					
Conceptual Knowledge (9-2)		A	B	C	*D	total	Alternative Conception
	A	0	0	2.3	10.3	12.6%	8c. The identity of the anode and cathode depends on the physical placement of the half-cells. (5)
	B	4.6	1.1	2.3	16.1	24.1%	8a. In standard reduction potential tables the species with the highest E^o value is the anode. (2)
					40.2		
	D	0	1.1	1.1	9.2	11.4%	3b. There is a high electron concentration at the anode. (1)
	total	13.8%	3.3%	6.8%	75.8%		

(1) Garnett & Treagust, 1992a; (2) Garnett & Treagust, 1992b; (5) Ozkaya, 2002.

Inert Electrodes in Electrolytic Cells

Using an inert electrode in an electrolytic cell presented a dilemma for more than half the students interviewed. According to Nancy, "There will be no transfer of electrons when using an inert electrode. They don't react with anything so there will be no transfer of electrons". Peggy explained when an inert electrode would be required, "When you don't have one of the half reactions and you need a cathode or an anode because the solution you might be using might be two reduction reactions rather than one reduction and one oxidation". Although Peggy had stated that oxidation and reduction reactions occurred together in the voltaic cell that she set up previously, this knowledge did not transfer to electrolytic cells.

Often students observe in experiments only what they expect based on their alternative conceptions and many of these are not changed by further instruction due to students' inability to interpret and understand the chemical phenomena at a particulate level of representation (Treagust et al., 2002). For example, Mary was holding her electrodes with tension on the wires and offered the following explanation for her observation:

[Mary] "Those two (electrodes) are attracted to each other."

[Interviewer] "Why do you say that those two are attracted?"

[Mary] "I don't know but it is pretty strong - the magnetic pull."

[Interviewer] "Are saying that there is a magnetic pull between the two electrodes?"

[Mary] "Yes. I think it is just because of the electrons that are being pulled through because it is attracting the carbon ions (from the inert electrode) in the solution towards the solid copper that is going to try and attract these electrons."

[Interviewer] "And you are feeling this physically?"

[Mary] "Yes."

[Interviewer] "Where did you learn that?"

[Mary] "From my observations and probably back to elementary school with positives and negatives and north and south poles."

In Mary's case, the unfamiliarity with an inert carbon electrode and prior knowledge of magnets lead to the development of an alternative hypothesis to account for an unexpected observation. Ms. Maloney recognized that she might have been contributing to this idea, "In grade 10, I use the idea of the north and south pole of magnets attracting to help them visualize how positive and negative ions attract in ionic compounds. It makes sense that they would extend that idea to here. Since I know that they are thinking along those lines, I see where I need to be more careful using examples to make sure that I am not causing these different idea or at least to make the problems with the idea more up front with my students".

Problem Solving Strategies in Electrolytic Cells

Students used a working-forwards strategy for modeling routine voltaic cells. They began the problem by using the redox table to select equations for the cathode and anode reactions and to calculate the predicted cell potential. They then selected their equipment to set up their routine cell based on their equations. When working with the non-standard cell designs; however, they used a means-ends strategy. For example, when selecting a single electrolyte to use in a voltaic cell, rather than referring to their equations to help them make a choice, 11 of the 19 students used trial-and-error to replace the electrolytes until the cell began to operate again. During an activity that students did in the laboratory in one school, students worked with voltaic cells that contained two metal electrodes and seemed to developed a decision routine to solve this type of problem. The steps in the decision routine that I observed during the activity were to use the redox table to write the equations and calculate the cell potential for each cell while sitting at their desks. They then moved to the laboratory benches to set up each cell with the metal in its ionic solution and to verify the cell potential that they had calculated. This decision routine did not apply to cells in which the metal electrodes were replaced with non-metal electrodes, so many students resorted to a means-ends problem-solving strategy when the procedure that they applied to routine cells proved to be inadequate. None of the students used a working-forwards strategy for electrolytic cells. In the pre-interview activity (see Table 3-15), 75% of students interviewed expressed a preference for quantitative problems involving the application of formulas, and all students attempted to apply qualitative decision routines without conceptual knowledge of the concepts or processes.

These findings could be due to the fact that problems that can be successfully solved using procedural knowledge were practiced extensively during the observed lessons and laboratory activities, which supports the conclusions of Niaz and Chacon (2003). Students at this level were preparing for provincial examinations leading teachers to work hard at preparing them and equipping them with the necessary skills that they felt would enable them to obtain good test scores. As Ms. Maloney explained, "These students are under a lot of pressure because of the diploma exams because the results impact their choices for next year. I try to give them lots of questions from old diploma exams for assignments and during tests so that they have a chance to practice interpreting the questions and know what to expect at the end of the term." Mr. Clarke agreed with her and added, "I try to schedule about two weeks at the end of the semester to work on practice exams so that my students really feel ready for the diploma. If they have enough time to practice then they will be ready for the exam". Mr. Smyth added, "It is often a matter of motivation. As they start to recognize patterns in the types of questions that are asked on the exams, they get more confident in what they can do. They work together to find out what is predictable and then come back after they have written the exam to talk about what was on it that they were expecting. It would be nice if they would look at the program outcomes like that rather than just the exam questions because then the whole course might seem more accessible to them". When asked if he went through this process with his students, he replied, I haven't taken the time to do it in the past with the students but it might also keep me honest about adding extra stuff that is not necessary in the course. A checklist would help them keep track of what they already know and what they need to work on for each unit rather than just during the exam review period. This would actually be a good way to start and end each unit so that they know what to expect and how close they are to getting where they need to be.".

Any problem, if rehearsed sufficiently in class, could facilitate the recognition of procedures or algorithms by the student (Niaz & Chacon, 2003); however, according to Piaget (1972), only those procedures developed by the students themselves would lead to understanding of the topic. This research study proposes that procedures used for both qualitative and quantitative problems can be approached using a reproducible method. The findings were consistent with quantitative problem solving studies by Bunce (1993), Nakhleh (1993) and Mason, Shell, and Crawley (1997), who found evidence that novice problem solvers (high school and undergraduate students) usually have greater success solving algorithmic-mode problems than problems having a more conceptual base in introductory chemistry. Niaz and Chacon (2003) found that mathematical transformations requiring formulas that were well rehearsed in class were more amenable to the construction of algorithms, and Niaz and Robinson (1992) concluded that training in algorithmic-mode problems does not guarantee learning of the conceptual base of chemistry. This study does not support the finding of Shuell (1990) in which he concluded that novice problem solvers usually have difficulty in solving problems because of a lack of prior knowledge in a specific content area, not because they simply lack the ability to solve problems. Students in this study had ability in working with individual concepts related to electrochemical cells but seemed unable to make meaningful connections between these concepts. The teachers in this study did provide numerous examples of applications of electrochemistry (5% of class time, see Table 4-15) in order to make the topic relevant and interesting, and 11.2% of the electrochemistry unit in *Nelson Chemistry* (1993) involved topics related to the interaction of science, technology and society (STS) (see Table 4-10). However, students seemed to treat these as additional facts to memorize, rather than as a contextual basis for the study of electrochemical cells. For example, Colleen explained, "The information boxes are interesting if you take time to read them but you don't need to know that stuff to get the questions right in class". The students tended to be very adept with facts and generalized procedures but did not seem to think in terms of integrated or applied knowledge.

Table 4-10. Coding analysis for the theme of the interaction of science, technology and society (STS) in *Nelson Chemistry*, 1993. Data is reported as percentage of total units of analysis.

	STS Theme	Total Units of Analysis	Percentage
Complete paragraphs	24	177	13.6
Questions	9	148	6.1
Figures	10	41	24.4
Tables with captions	2	1	20.0
Margin comments	6	27	22.2
Laboratories/Activities	0	52	0
Total	51	455	11.2

Note: units of analysis included complete paragraphs, questions, figures, tables with captions, margin comments, and complete steps in laboratory or hands-on activities

Pushkin (1998) found that some of those who teach introductory chemistry and physics place more value on procedural learning than on conceptual learning, giving learners the impression that science is "math in disguise". If an appreciation of the rational criteria for the development of the tools used for decision making was an epistemological goal of teaching electrochemistry (e.g., the development of the redox table), students may be able to contextualize their knowledge more coherently rather than relying on memorizing, applying a decision routine, or inappropriately incorporating prior knowledge. Indeed Koslowski (1996) concluded that for students to achieve scientific understanding, both data and the theory of underlying mechanisms were needed for successful causal reasoning. Understanding expertise can provide insights into the nature of thinking and problem solving. It is not simply general abilities, such as memory or intelligence, nor the use of general strategies that differentiate experts from novices. Experts have acquired extensive conceptual knowledge that affects what they notice and how they organize, represent, and interpret information in their environment (Barnett & Koslowski, 2002; Bransford et al., 1999). This, in turn, affects their abilities to remember, reason, and solve problems. Experts' knowledge cannot be reduced to sets of isolated facts but reflects contexts in which these facts can be applied (Barnett & Koslowski, 2002).

Conceptual knowledge can be encouraged by aiding student construction of relationships among pieces of information, identifying relevant prior knowledge and confronting alternative conceptions. Among the benefits of linking procedural knowledge with conceptual knowledge are better retention of information and easier transfer of procedures to new contexts. For example, students may be expected to remember that both cations and electrons move towards the cathode. A procedural knowledge test item for this information could contain a diagram of a voltaic cell with numbered arrows for the student to identify (e.g., see Figure 3-2). Students with conceptual knowledge of voltaic cells would also understand why the particles have particular properties. They could start by knowing that an electrochemical cell contains two half-cells, each containing a solid and a solution and that the substances in the half-cells must have different abilities to attract electrons. However, by learning the relationships between the structure and function of electrochemical cells, students with conceptual knowledge may be more likely to be able to use what they have learned to solve novel problems—to show evidence of transfer. For example, imagine being asked to design an electrochemical cell from household substances. Would there have to be two solutions? Why or why not? An understanding of reasons for the properties of electrochemical cells suggests that solutions may not be necessary—perhaps sandwiching the pieces of metal between damp paper towels would provide a conduit for particle movement and be the source of the electrolyte. An activity suggested by Mr. Weber was to replace the lab equipment with more common apparatus. "I used lab that does what we are talking about. They used clay flower pots, sharpened pencils, and table salt. Since these things don't look like your standard porous cups, electrodes, and electrolyte, we could focus on get at what they know about the function of the materials rather than the developing a lab skill." Meaningful learning of electrochemical cells does not guarantee an answer to design questions, but it does support thinking about alternatives requiring conceptual knowledge that is not readily available if one only applies procedural knowledge (Bransford & Stein, 1993). Knowing how the concepts interact within the context of the entire process is as important as knowing individual concepts (Resnick & Resnick, 1992).

Bodner and Herron (2002) suggested that novices approach all problems the same way – looking for an algorithm that fits their interpretation of the question. They proposed that a way around this difficulty was to solve problems with students, instead of for them. By asking students what steps should be taken to solve the problem, rather than running through the steps as they watch, the focus will change from teaching problem-solving skills to building them with the students. However, Renkl and Atkinson (2002) caution that the extent to which learners' profit from the study of examples depends on how well they explain the solutions of the examples to themselves. This allows them to recognize problem contexts in addition to problem solutions. The teachers identified a possible problem with following this process. Mr. Smyth explained, "I work out a few examples on the board with them so that they understand the basic strategy and then assign similar practice problems to do on their own. This works well for one type of problem …They struggle on tests because the problems are mixed – not in the same order as their notebook. I think we need to be more up front about what to look for to identify different types of problems and then help them see which strategy they need to apply in different situations. I don't do that with them now but it makes sense to work through it with them. I just take it for granted that they know to do this but it looks like I am assuming too much here."

Conceptual knowledge questions can be a focus for laboratory activities. The holistic question on the Chemistry 30 diploma examination requires students to design, compare or explain, rather than to verify. For example, the June 2003 holistic question, which was based on a description of different fuels that could be used in a specific camping stove described in a scenario box, was "Design an experiment that would allow you to choose the best fuel for heating water on the XGK stove" (Alberta Education, 2005b). Teachers who participated in the group interview indicated that they did not use labs with this focus, and in the textbook that they predominantly used, 82.6% of laboratory activities were either confirmation or structured inquiry laboratories (see Table 4-11).

The teachers did discuss ways to change their current activities to approach this different perspective. For example, Ms. Maloney suggested giving the students the materials that were used in the voltaic cell lab but asking them to decide how the metals could be arranged based on their ability to attract electrons rather than confirming cell potentials. This would require procedural knowledge if the redox table was used, but conceptual knowledge would be required if the tools required for the student's decision routines were deemphasized. The teachers also discuss a variety of possible topics that could be used for design labs that could get students thinking about the function of the different components of an electrochemical cell. For example, Mr. Clarke suggested asking students to design a lab to "determine if a metal or an inert electrode would produce a higher voltage in a voltaic cell in order to have them explore properties of electrodes". Ms. Maloney recommended having the students set up voltaic cells prior to writing equations to allow them to explore which reactions were occurring using coloured electrolytes to show movement in the salt bridge. Although Mr. Smyth worried that such "design experiments would take longer than the labs currently used in the program because students would need to first develop procedural skills in order to begin successfully designing their own labs". Mr. Smyth suggested, "Maybe they need to make mistakes and then figure out how to fix them in order to want to do more than memorize the steps. We already do three titration labs and the students are much faster in the second and third ones as they get more confident with the equipment so this may not take as long as we think." Indeed, after searching through the textbook used for teaching, he could only find one lab that asked students to design an apparatus and none that required them to develop their own experimental question. Mr. Clark reflected, "I try to choose activities for my students that will show the concept I am teaching but it really is just another way of lecturing at them; more active but the same approach. The labs that I did at university were all of this nature and since I am trying to prepare them for the next level of education I thought that if they became familiar with this format it would be easier for them in the long run. After looking at what you found, it looks like we are doing a good job of teaching them to be technicians but not doing well when it comes to helping them think in new situations". Mr. Smyth compared the results of the diagnostic test to his unit test results, "My students' scores for the procedural knowledge questions were closer to my unit tests than the conceptual ones. Most of my questions are more analytical in nature with one correct answer. I usually get my students to explain the "what" aspect rather than trying to get them to address the "why" aspect of a concept." Ms. Maloney and Mr. Weber agreed with him and since they both liked the activities used in the task-based protocol with voltaic cells they decided to work together to modify it and design questions that would guide lab groups through the process and then try to design evaluation questions that would value this type of knowledge.

Table 4-11. Coding analysis of level of inquiry in laboratory activities in the electrochemistry unit in *Nelson Chemistry*, 1993. Data is reported as percentage of the total units of analysis.

Inquiry Level		Percentage
I	Confirmation	52.2
II	Structured inquiry	30.4
III	Guided inquiry	17.4
IV	Open inquiry	0

Note: units of analysis represent complete laboratory activities.

Lessons that required students to differentiate between contexts, and identify and evaluate their decision routines in each context, could promote the development of students' conceptual knowledge.

Category II: Levels of Representation of Knowledge in Chemistry

Overview of Category II Analysis

The level of representation of knowledge used by students was related to the type of problem being solved. For routine problems, about 58% of students used two or three levels of representation when predicting or explaining (see Table 4-12). For non-routine cells, those which involved novel problems, the majority of students used only one level of representation of knowledge and only 15% of students used two or three levels when making predictions or offering explanations about their electrochemical cells (see Table 4-13). Students were most familiar with routine cells because these were employed predominantly for examples during lessons and practice problems, in the textbook, and during laboratory activities.

According to Gabel (1998), conceptual knowledge in chemistry involves the ability to represent and translate chemical problems using three forms of representation: macroscopic, particulate, and symbolic. In their comprehensive review on problem-solving research in chemistry, Gabel and Bunce (1994) suggest that one of the main reasons students have difficulties solving some chemical problems is that they lack understanding of the connectivity of the concepts needed to solve the problems (see Figure 4-1).

Most students were successful with each of the three levels of representation when considered individually. At the symbolic level, the pattern of the location of oxidizing and reducing agents on a redox table was used to predict and write equations for reactions that would occur. At the macroscopic level, they could set up the copper-zinc voltaic cell and make correct observations while it operated. At the particulate level, they were able to discuss the movement of anions, cations and electrons. Their difficulty arose, however, because they did not connect the three levels of representation. Without this connectivity, students may be able to demonstrate procedural knowledge when making predictions or observations but have little conceptual knowledge of the underlying processes that involve the movement of electrons and ions to generate electrical energy.

De Jong and van Driel (2001) proposed that symbolic representation provided the interface between the macroscopic and particulate representations (see Figure 2-2). In this study, the relationship between the levels of representation had more than one interface (see Figure 4-1), and this depended on the type of problem being addressed by the student (see Tables 4-12, 4-13, and 4-14).

When predictions were made for routine voltaic cells, 42% of students used symbolic representation only, and 32% of students included all three levels. The macroscopic level only was used to make predictions by 84% of students for non-routine voltaic cells, and 74% of students for electrolytic cells. The majority of students made observations using the macroscopic level only; however 11% of students included the particulate level of representation when observing their cell operating (see Table 4-14). As Conor observed his cell he stated, "The copper solid is forming here so the electrons must be going in this direction for reduction to occur". For explanations about routine voltaic cells, 37% of students used the particulate level only and 53% of students included all three levels in their explanation (see Table 4-12). For non-routine voltaic cells, 79% of students used the particulate level only and 5% used both the macroscopic and particulate levels (see Table 4-13). Similarly for electrolytic cells, 78% of students used the particulate level only and 11% used both the macroscopic and particulate levels (see Table 4-14).

Table 4-12. Levels of representation of knowledge used by students for routine voltaic cells in the prediction, observation or explanation stage of the task-based interviews. Data reported as percentages (n=19).

Levels of Representation	Predict	Observe	Explain
Macroscopic only	11	100	0
Symbolic only	42	0	5
Particulate only	0	0	37
Macroscopic & symbolic	0	0	0
Symbolic & particulate	5	0	0
Macroscopic & particulate	11	0	5
Macroscopic, symbolic, & particulate	32	0	53

Table 4-13. Levels of representation of knowledge used by students for non-routine voltaic cells in the prediction, observation or explanation stage of the task-based interviews. Data reported as percentages (n=19).

Levels of Representation	Predict	Observe	Explain
Macroscopic only	84	95	0
Symbolic only	0	0	5
Particulate only	0	0	79
Macroscopic & symbolic	0	0	0
Symbolic & particulate	0	0	0
Macroscopic & particulate	11	5	11
Macroscopic, symbolic, & particulate	5	0	5

Table 4-14. Levels of representation of knowledge used by students for electrolytic cells in the prediction, observation or explanation stage of the task-based interviews. Data reported as percentage (n=19).

Levels of Representation	Predict	Observe	Explain
Macroscopic only	74	89	5
Symbolic only	11	0	0
Particulate only	0	0	78
Macroscopic & symbolic	5	0	0
Symbolic & particulate	5	0	0
Macroscopic & particulate	0	11	11
Macroscopic, symbolic, & particulate	5	0	5

Students were most familiar with routine voltaic cells (see Table 4-15) and seemed to have developed decision routines based on procedural knowledge to solve problems.

Students used a strategy that could be described as a working-forwards problem-solving strategy to solve the routine voltaic cell problem: use the redox table to write an equation, and then use the assembled apparatus to trace the pathway of charged particles through the cell. They used procedural knowledge that included definitions, acronyms and decision routines that allowed them to offer predictions and explanations that included the three levels of representation without necessarily having conceptual knowledge of the operation of the cell. For non-routine voltaic cells and electrolytic cells, students resorted to a trial-and-error strategy by assembling the apparatus in different ways until it began to operate and then developing an explanation of the operation based on what they observed.

Table 4-15. Amount of time given to electrochemical cell concepts during the 16 classroom observation periods

Lesson Topic	Percent of Lessons in Classes Observed
Routine voltaic cells	70
Non-routine voltaic cells	5
Electrolytic cells	20
Applications of cells (STS)	5

Students were proficient with the symbolic representation for voltaic cells but did not transfer this information to the other two levels. Rather, it was necessary to make these connections explicit when solving problems with students during the task-based interview because students had limited ability to do this step intuitively. For example, Jayne correctly predicted the half-reaction that would occur at the cathode of her voltaic cell and used the symbolic level to write an equation: $Cu^{2+}_{(aq)} + 2\,e^{-} \rightarrow Cu_{(s)}$. She was struggling; however, to identify the solid that she observed forming on the copper electrode in her voltaic cell, "Since electrons move from anode to cathode, the product of copper solid, or the zinc, will be built at the copper. That is where I get confused. I am not always sure what builds at the cathode just by looking here (at the electrode). It is not an ion that will be building up so it must be the copper solid". Even though she had already used symbolic representation with her half-reaction equations, she did not have the conceptual knowledge to recognize the connectivity between these two forms of representation.

Ruth was also unable to transfer among the three levels of representation of knowledge with voltaic cells. After observing that solid copper formed at the cathode in her cell, she struggled to explain why this occurred.

[Interviewer] "Why did the copper solid form?"

[Ruth] "Because it reacted"

[Interviewer] "What did it react with?"

[Ruth] "With the zinc"

[Interviewer] "What did the zinc provide during this reaction?"

[Ruth] "I'm not sure"

[Interviewer] "Let's look at your equations. What were the products of the zinc half-reaction?"

[Ruth] "Zn^{2+} and two electrons"

[Interviewer] "How were those two electrons used in this reaction?"

[Ruth] "I don't know."

Although Ruth had defined the processes of oxidation and reduction and talked about the movement of electrons in voltaic cells which represented knowledge at the particulate level, the connectivity between her observations at the macroscopic level, electron and ion movement at the particulate level, and the half-reaction equations at the symbolic level, were not explicit for her.

Colleen used the particulate level of representation when asked, "Could you describe the movement of the charged particles that you can't see in your electrolytic cell?" She explained

> Well this is electrolysis and this is the cathode (copper electrode) which means it must be undergoing reduction so it is gaining electrons so the battery is supplying the electrons therefore it is becoming more negative which is drawing the copper (ions) from the solution. This one (carbon anode) is releasing electrons into the battery and it is becoming more positive so it is drawing the negative SO_4 ions towards the inert (electrode). And this is also becoming positive (copper cathode) and this is becoming negative (carbon anode).

Colleen's explanation revealed that she did not relate the symbolic and particulate levels of representation. She offered the following alternative theory of the process occurring in her electrolytic cell.

[Interviewer] "What do you see?"

[Colleen] "I see bubbles. What is that? Steam?"

[Interviewer] "Why did you say it was steam?"

[Colleen] "Because it looks like steam - it is beginning to evaporate."

[Interviewer] "Are you saying that the water is evaporating?"

[Colleen] "Yes and you can also see that the water level is reduced; it is lowering. It is getting turned to steam because the water is getting heated because of the electrons or because this is undergoing oxidation so that is losing the electrons so they are turning into ions and they are rising because they are turning into gas"

[Interviewer] "What are the ions?"

[Colleen] "I don't know"

[Interviewer] "Is there some way to look it up?"

[Colleen] (looking at the oxidation of water on the redox table) "It must be oxygen because hydrogen (ion) is left in the solution because it's aqueous"

[Interviewer] "So what is it that we are seeing rising?"

[Colleen] "Oxygen (gas)"

[Interviewer] "Why did you think it was steam?"

[Colleen] "I guess it just looked like steam and it looks like when you are with a fire, like when you have a boiler on, and the steam rises, that looked like it."

Colleen was able to develop a detailed explanation of her observations in the cell using macroscopic and particulate representations combined with her everyday experience, but her explanation above seems to indicate that she did not relate it to the symbolic level until guided to do so.

Students' Explanations of Voltaic Cells

Three students with conceptual knowledge of particle movement in voltaic cells attributed their ability to learn this abstract concept to the use of animations which is supported by the findings of a number of studies that have explored methods to improve the ability of students to transfer between levels of representation in chemistry (e.g., Low & Sweller, 2005; Velazquez-Marcano, Williamson, Ashkenazi, Tasker, & Williamson, 2004; Yang, Andre, & Greenbowe, 2003). Jayne explained that although demonstrations were useful, doing the animations was better because "when you are doing it on paper it is very abstract. You don't actually see the ions whereas when you are using the animation it forces you to think about what is happening as you are doing it." An animation used in one class was a video (TV Ontario, 1996) that showed circles presenting electrons, cations, and anions moving in an electrolytic cell. For example, electrons were shown to move along the wire and then join with the cations at the cathode. A colour change represented a change in state as the cations were reduced to atoms of the metal. A wide variety of videos of animations are available on the web by searching using the key words, voltaic cell animations.

Students did not seem to intuitively relate the symbolic and macroscopic representations of knowledge, often not looking at equations that they had written in order to make predictions about what they would see in their cells. This was particularly true for non-routine voltaic cells and electrolytic cells. Two laboratory activities were observed during classroom observations in this study. One was a lab to observe spontaneity of reactions and this information was used to set up a reduction half-reaction table with the four metals used in the activity. In the second activity, students wrote equations and calculated cell potentials for four voltaic cells and then set them up to measure the cell voltage. The focus of these laboratory activities was the verification of a concept rather than engagement with ideas. As Mr. Weber explained, "labs reinforce the material covered in the lessons". For example, for the voltaic cell lab, students practiced symbolic representations using equations, and macroscopic representations while observing the cells. However, there was no requirement to attempt to address why the voltaic cell was operating to produce a voltage. Indeed, as the teachers' group discussed the activities that they used to teach electrochemistry, it became apparent that lessons focused instruction on ways to help students master decision routines. For example, as students were learning to predict the reactions for both voltaic and electrolytic cells, Mr. Clark reminded them, "The process is exactly the same as when we wrote these equations before learning about these cells. You use the five-step method." He listed the steps with the students before starting to work with the redox half reactions on both occasions. Ms. Maloney had the five steps listed on a poster at the front of the room and frequently directed her students' attention to it when solving problems with them, "If you can't remember the steps just look right here. We follow the same steps every time we need to write an equation using the redox table in the entire unit". However, as this was the final year of high school for the majority of students, Mr. Smyth recognized that, "The kids just want to get good grades to get into university. They want to know how to get the right answer but don't want to spend too much time doing it because they have busy lives outside of school". To promote conceptual knowledge development, it may be necessary to refocus teaching and learning strategies to decrease the value of procedural knowledge.

Category III: Alternative Conceptions

Overview of Category III Analysis

In addition to problems arising from a limited ability to make connections between concepts in chemistry, research has found that students tend to ignore instruction that does not coexist well with their existing knowledge, or they will reinterpret the information to match their prior expectations from previous exposure to the information (Driver & Easley, 1978; Wandersee et al., 1994).

The alternative conceptions held by students were typically the result of overgeneralizations of prior knowledge. The categories of the alternative conceptions confirmed or uncovered in this study are listed below.

- complete circuits and movement of charged particles
- electrode characteristics
- everyday meanings for scientific vocabulary
- redox reactions and the redox table
- new alternative conceptions

The student interviews were used to confirm that the alternative conceptions identified in the main study diagnostic instrument were held by students and to infer their source. Student interviews verified that 54% of the alternative conceptions used as distractors in the diagnostic instrument were held by the students who participated in this study (see Table 4-16).

Table 4-16. Electrochemistry alternative conceptions used to develop the distractors for questions in the main study diagnostic instrument. Alternative conceptions in red were verified in the interview part of the study and those in black were not observed in the interviews (n=87).

Alternative Conception	Question and Distractors in the Diagnostic Instrument	% of Students Choosing Alternative Conception
1a	6-2D	5.7
1b	5-2A	9.2
2d	5-2B	5.6
2e	5-2A and 5-2B	9.2
2f	5-2B	5.6
3b	5-2C and 9-2D	21.8 + 11.4
3c	5-2C	21.8
4a	4-1B	7.9
4b	4-1C	5.7
4c	4-1D	4.5
5a	4-2A	29.8
6	4-2B and 4-2C	10.3 + 9.1
8a	7-1A and 9-2B	24.1 + 4.5
8b	2-2C and 3-2A	15.9 + 6.8
8c	9-2A	12.6
8d	6-2A and 6-2B	1.1 + 27.6
9a	1-2D	16.0
9c	1-2B and 1-2C and 2-2A	32.1 + 2.3 + 19.4
10a electrolytic only	7-2C	2.2
10b	7-2A	6.8
10c	7-2D	22.9
11a	6-2B	27.6
11b	6-2A	1.1
12d	10-2A	2.3
13a	10-2C	3.3
13e	10-2B	29.9
No mole ratio	8-2C	21.8
Inverted mole ratio	8-2D	5.6

Note: When the alternative conception was used for more than one question or distractor, the question and percentage of students choosing the distractor are identified separately and sequentially. See Appendix C for the main study diagnostic instrument and Appendix D for alternative conception codes.

Complete Circuits and Movement of Charged Particles

Students should have had prior knowledge about complete circuits from their everyday experience with household electricity and previous school science (Alberta Education, 1996; 2003; 2007a). For example, when studying circuits in grade 9, students should have learned that a continuous flow of electrons allowed an electrical device, such as a lamp, to operate. In grade 10, a light bulb was used in a conductivity device to show that ionic compounds conduct electricity. This prior knowledge may have been applied to voltaic cells. When Ruth was asked if electrons stop at the cathode, she replied, "They keep moving in the circle. They go from the copper and then over to the zinc. They are passing through the solids, through the solution, through the other solid, to the voltmeter. The current is a complete circle and the electrons are being supplied throughout the whole circle".

The circuit in a voltaic cell was indeed completed as charged particles moved in a complete circuit; however, the type of charged particle moving depends on the specific location in the cell. Only electrons moved through the connecting wire, attracted towards the species with the highest electron potential (ability to attract electrons). Only ions move through the electrolyte. As the cell operated, an imbalance of charge occurred because of the chemical reactions and the ions moved through the electrolyte to maintain electrical neutrality in the cell. As electrons moved towards the cathode, the electrode became relatively more negative than the surrounding electrolyte, which in turn attracted cations – positively charged ions. Similarly, as electrons moved away from the anode, it became more positive relative to the electrolyte, which in turn attracted anions – negatively charged ions. Three questions in the main study diagnostic instrument, 5-2 (see Figure 4-14), 6-2 (see Figure 4-15) and 7-2 (see Figure 4-16), were designed with distractors using alternative conceptions about electron and ion movement in voltaic cells. In order to explore students' conceptual knowledge, non-routine voltaic cells were used in the task-based interview.

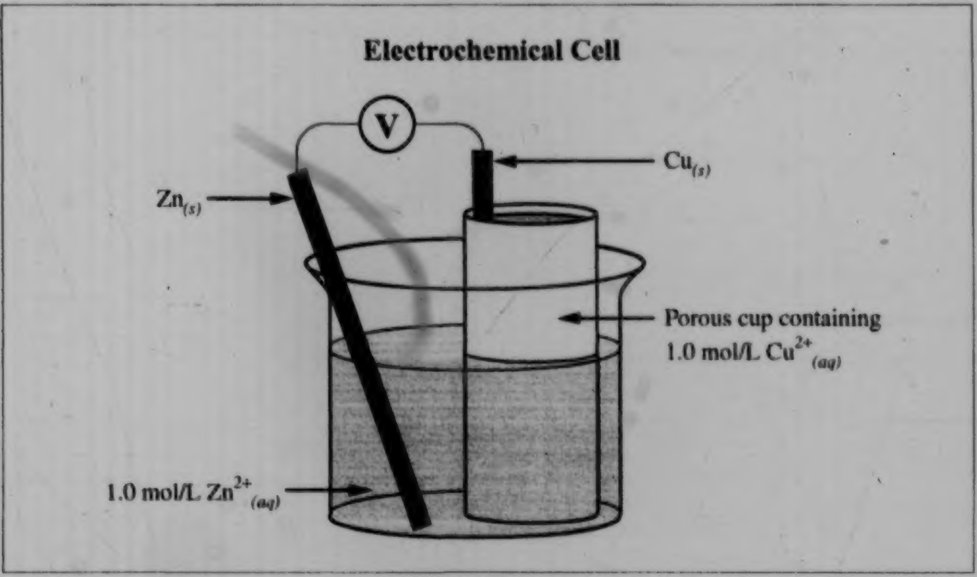
For question 5-2 (see Figure 4-14), the 9% of students who selected alternative A (see Table 4-17), and 16% of students in the interview held the alternative conception that electrons move through electrolytes by being attracted to positive ions in solution. Indeed, 53% of students believed that electrons flow in electrolytes. Ed explains, "Because the sodium is positive it allows the electrons to go from one sodium (ion) to the next through the solution. They travel from the copper electrode through the solution to the zinc electrode to complete the circuit". Information that may have been learned in previous science courses about electrical circuits and everyday knowledge about household electricity may have resulted in a transfer of information to a context in which it did not apply.

For question 5-2 (see Figure 4-14), the 22% of students who selected alternative D (see Table 4-17), and 16% of students interviewed held the alternative conception that there was a high electron concentration at the anode. For example, Jayne explains, "I know that they (electrons) are moving from anode to cathode and I wrote out the electron potentials. It looks like it is moving from a higher concentration of electrons or electron voltage to a lower concentration of electrons". Quinn talked about electrons "building up around the zinc (anode)" and Olivia explained that "electrons travel through the wire because they are repelled by the excess electrons at the anode". Students were generally not aware that electron movement is almost instantaneous and no reference was found about the rate at which these reactions occur in either of the textbooks that these students used (e.g. *Addison-Wesley Chemistry*, 1993; *Nelson Chemistry*, 1993) or other teaching resources. Students may have been familiar with increases in the concentration of products during the progress of a chemical reaction from their school science lessons in the chemistry sections in grade 9, 10 and 11 and this was likely a logical extension of that concept.

The alternative conception that there is a low electron concentration at the cathode was held by 22% of students who selected alternative D for question 5-2 (see Figure 4-14 and Table 4-17), and 16% of students interviewed. Nancy explained that "electrons are not produced here (cathode) so there would not be very many in the solution".

Figure 4-14. Two-tiered question 5 in the main study diagnostic instrument.

Use the following information to answer the next two questions.


Electrochemical Cell
V
$Cu_{(s)}$
$Zn_{(s)}$
Porous cup containing 1.0 mol/L $Cu^{2+}_{(aq)}$
1.0 mol/L $Zn^{2+}_{(aq)}$

5-1. The cell potential for the electrochemical cell in the diagram above is

A. +1.10 V
B. +0.42 V
C. –0.42 V
D. –1.10 V

5-2. In the electrochemical cell above electrons move through the

A. electrolyte because they are attracted to the positive ions in the solution
B. electrolyte in one direction and protons move through the electrolyte in the opposite direction
C. wire from the electrode with the lower reduction potential to the electrode with the higher reduction potential
D. wire from the electrode with the high concentration of electrons to the electrode with the low concentration of electrons

---

Table 4-17. Cross-tabulation analysis of two-tiered question 5 in the main study diagnostic instrument. Data reported as percentage of students selecting the correct answer (n=87).

		Procedural Knowledge (5-1)					
Conceptual Knowledge (5-2)		*A	B	C	D	total	Alternative Conception
	A	7.0	1.1	0	1.1	9.2%	1b. Electrons move through electrolytes by being attracted to positive ions in solution. (1) 2e. Electrons flow in electrolytes. (1)
	B	3.4	0	1.1	1.1	5.6%	2d. Protons flow in electrolytes (regardless of whether the solution is acidic, basic or neutral). (1) 2e. Electrons flow in electrolytes. (1) 2f. Protons and electrons flow in opposite directions in an electrolyte. (1)
	[redacted]	58.6	[redacted]	[redacted]	[redacted]	[redacted]	
	D	18.4	0	0	1.1	21.8%	3b. There is a high electron concentration at the anode. (1) 3c. There is a low electron concentration at the cathode. (1)
	total	87.4%	2.2%	2.2%	7.9%		

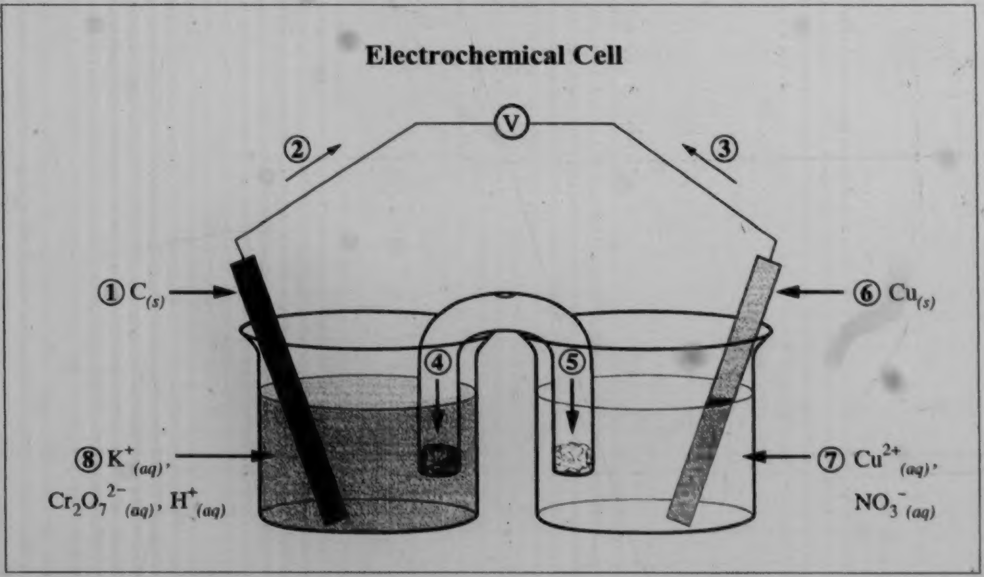
(1) Garnett & Treagust, 1992a.

For question 6-2, the 6% of students who selected alternative D (see Figure 4-15 and Table 4-18), and 16% of students interviewed believed that anions and cations attract each other and this affects the movement of ions to the electrodes. For example, Dan explained that "The ions are coming to the centre because they are attracted to each other", and Mary believed that sodium ions in the salt bridge moved towards both electrodes because "they were attracted to the sulfate ions in the electrolyte in the two half-cells". This alternative conception may be caused by overgeneralizing information about ionic compounds. For example, a common description of an ionic compound found in a grade 9 textbook (*Science Focus 9*, 2005) was "positive sodium ions attract negative chloride ions to form a cube-shaped arrangement in sodium chloride". This attraction applies to solids, not to solutions of ionic compounds in which the ions have been dissociated. Ms. Maloney used this type of explanations to explain precipitate formation observed during a spontaneous reaction when a student has used an inappropriate substance in the salt bridge of their voltaic cell during a laboratory activity, "The two aqueous ions are attracted to each other in the solutions but together they form an insoluble product. That is the precipitate that you see and it will eventually stop the voltaic cell from working properly because it changes the solution concentration".

For question 6-2, the 28% of students who selected alternative B (see Figure 4-15 and Table 4-18), and 26% of students interviewed held the alternative conception that the anode is negatively charged and because of this it attracts cations, and that the cathode is positively charged and because of this it attracts anions. Helen explains, "The cathode is positive because if it was really negative the electrons would be repelled". When asked where she learned this she replied, "In physics because opposite charges attract and like charges repel". When Patrick was asked to talk about the cations and anions in the cell he explains, "The negatives, the anions are moving towards the zinc. Zinc is the anode, and it is negative because it is losing its electrons. The copper is positive because it is gaining the positive cations". Both students have overgeneralized prior knowledge. Helen is using theory related to magnets from elementary science classes (Alberta Education, 1996) and everyday experience, and Patrick is using electrostatic attraction from chemistry (Alberta Education, 2003, 2005a) class to make this abstract topic meaningful.

Figure 4-15. Two-tiered question 6 in the main study diagnostic instrument.

Use the following information to answer the next two questions.


Electrochemical Cell
V
②
③
① $C_{(s)}$
⑥ $Cu_{(s)}$
④
⑤
⑧ $K^+_{(aq)}$, $Cr_2O_7^{2-}{}_{(aq)}$, $H^+_{(aq)}$
⑦ $Cu^{2+}_{(aq)}$, $NO_3^-{}_{(aq)}$

6-1. Which of the following statements applies to the electrochemical cell above?

A. The anode is labelled 1

B. Electron flow is labelled 2

C. Cation movement is labelled 4

D. The strongest reducing agent is $Cr_2O_7^{2-}{}_{(aq)}$ and $H^+_{(aq)}$

6-2. Which of the following statements applies to the electrochemical cell above?

A. Protons are attracted to the anode because it is negatively charged

B. Electrons are attracted to the cathode because it is positively charged

C. Cations move towards the cathode so that the cell remains electrically neutral.

D. Cations are attracted to anions in the electrolyte which limits their movement toward the cathode.

Table 4-18. Cross-tabulation analysis of two-tiered question 6 in the main study diagnostic instrument. Data reported as percentage of students selecting the correct answer (n=87).

		Procedural Knowledge (6-1)					
		A	B	*C	D	total	Alternative Conception
Conceptual Knowledge (6-2)	A	1.1	0	0	0	1.1%	8d. Anodes, like anions, are always negatively charged; cathodes, like cations, are always positively charged. (5) 11b. The anode is positively charged because it has lost electrons. The cathode is negatively charged because it has gained electrons. (2)
	B	4.6	2.3	18.4	2.3	27.6%	8d. Anodes, like anions, are always negatively charged; cathodes, like cations, are always positively charged. (5) 11a. The anode is negatively charged and because of this it attracts cations. The cathode is positively charged and because of this it attracts anions. (2)
	[redacted]	[redacted]	[redacted]	49.4	[redacted]	[redacted]	
	D	2.3	0	3.4	1.1	5.7%	1a. In a cell the anions and cations attract each other and this affects the movement of ions to the electrodes. (1)
	total	8.0%	11.5%	70.1%	10.2%		

(1) Garnett & Treagust, 1992a; (2) Garnett & Treagust, 1992b; (5) Ozkaya, 2002.

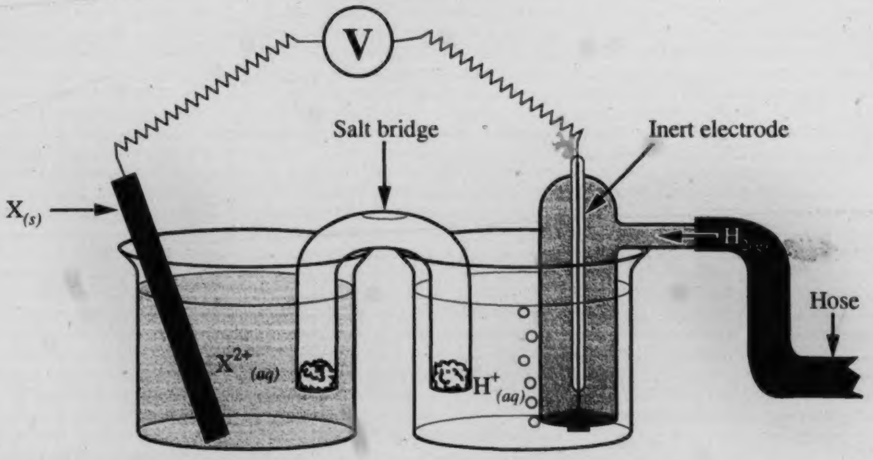
For question 7-2, the 2% of students who selected alternative C (see Figure 4-16 and Table 4-19), and 53% of students interviewed held the alternative conception that electrons enter the electrolyte at the cathode, move through the electrolyte between the electrodes, and emerge at the anode. This conception was the result of overgeneralization of prior knowledge about electrical circuits. The evidence and discussion of this topic appears earlier in this chapter (see pp. 174-176).

Twenty three percent of students who selected alternative D in question 7-2 (see Figure 4-16 and Table 4-19), and 16% of students interviewed held the alternative conception that the salt bridge assists the flow of current (electrons) because positive ions in the bridge attract electrons from one half-cell to the other cell. This alternative conception may have been the result of overgeneralizing attractive forces between ions, a topic learned in prior chemistry classes. The evidence and discussion of this topic appears earlier in this chapter (see pp. 179-180).

Figure 4-16. Two-tiered question 7 in the main study diagnostic instrument.

Use the following information to answer the next two questions.

Electrochemical Cell



In this apparatus, the anions in the solution move from the hydrogen half-cell solution into the salt bridge and migrate toward the $X_{(s)}$ electrode.

7-1. If the voltmeter reads +0.40 V under standard conditions, then $X_{(s)}$ is most likely

A. $Ag_{(s)}$
B. $Al_{(s)}$
C. $Cd_{(s)}$
D. $O_{2(g)} + H_2O_{(l)}$

7-2. Which of the following statements describe the circuit in the electrochemical cell above?

A. The salt bridge supplies electrons to complete the circuit.
B. An operating circuit requires the movement of anions, cations and electrons.
C. Electrons enter the electrolyte at the cathode, move through the electrolyte, and emerge at the anode.
D. The salt bridge assists the flow of electrons because positive ions in the bridge attract electrons from one half-cell to the other half-cell.

Table 4-19. Cross-tabulation analysis of two-tiered question 7 in the main study diagnostic instrument. Data reported as percentage of students selecting the correct answer (n=87).

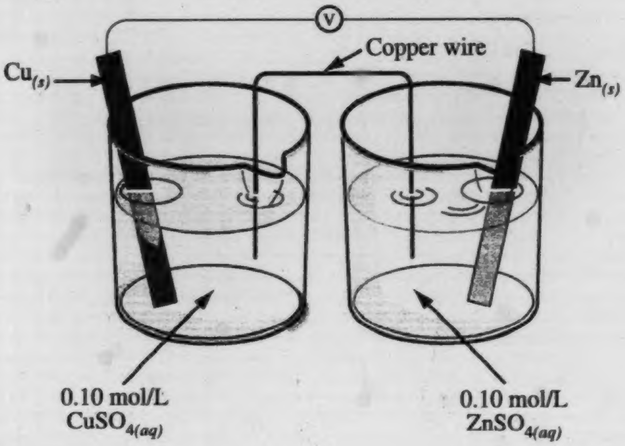
		Procedural Knowledge (7-1)					
		A	B	*C	D	total	Alternative Conception
Conceptual Knowledge (7-2)	A	1.1	0	3.4	2.3	6.8%	10b. The salt bridge supplies electrons to complete the circuit. (2)
				44.8			
	C	0	0	1.1	1.1	2.2%	10a. Electrons enter the electrolyte at the cathode, move through the electrolyte, and emerge at the anode. (2)
	D	2.3	0	12.6	8.0	22.9%	10c. The salt bridge assists the flow of current (electrons) because positive ions in the bridge attract electrons from one half-cell to the other cell. (2)
	total	4.5%	0%	61.9%	33.2%		

(2) Garnett & Treagust, 1992b.

Probing Conceptual Knowledge with Non-Routine Voltaic Cells

Non-routine voltaic cells were used to probe the type of knowledge that students used when attempting to solve novel problems. After completing a task-based activity with a routine copper-zinc voltaic cell, students were first asked, "If the salt bridge is removed, do you think the voltmeter will show a reading or not? Explain." All students believed that the salt bridge was a necessary component. Next they were asked, "If the salt bridge is replaced with a copper wire, do you think that the voltage will be different from the voltage obtained when a salt bridge is used? Explain." After making each prediction, students were asked to assemble the cell (see Figure 4-17) to test their prediction.

Figure 4-17. A representation of the copper-zinc voltaic cell with a copper wire replacing the salt bridge that students assembled during the task-based interview



Although 75% of students interviewed predicted that the voltaic cell would stop operating, the remainder believed that a circuit would continue through the copper wire. Liam predicted, "The voltage might be lower because the ions are not moving. Zinc ions are supposed to be moving towards the copper (electrode) as well and if we leave it in here long enough we might be able to see Zn^{2+} building up on the outside. The zinc ions can't move across the wire". He believed that without the movement of ions something else had to be moving to complete the circuit and cause a reading on the voltmeter. Olivia decided that ions can move through the wire but "the voltage will be lower because they are not going as fast because the wire is smaller than the U-tube". Even though both students stated that the salt bridge was necessary for an operating voltaic cell, they believed that somehow a charged particle would complete the circuit.

Over 60% of students (12 of 19 students) believed that it was the function of the ions in the electrolyte to transport the electrons so that the circuit could be completed. After assembling a copper-zinc voltaic cell and making observations, students were asked to talk about what happened to the electrons when they reached the cathode. According to the half-reactions written by the students, the electrons were consumed during the reduction of copper(II) ions to form solid copper. However, the explanations indicated that prior knowledge related to circuits and chemical bonding influenced the framework they constructed to understand the abstract nature of voltaic cells. Dan recognized that a complete circuit was present because he could see a voltage on the voltmeter and explained how electrons were completing this circuit.

> It has to do with the transfer of electrons between ions in the solution because copper (ions) would still get the electrons from the copper electrode and (solid) zinc would steal electrons from the copper metal creating more ions which steal more electrons through this circuit. The electrons piggy-back across the ions between the electrodes to complete the circuit. The ions keep the electrons from each other.

Even though he had written a reduction half-reaction equation that represented electrons being removed from the system and had observed the production of solid copper which verified that this reaction had occurred, he still believed that the electrons must be moving in a circle through the electrolyte and back to the zinc electrode for the circuit to be complete.

An alternate explanation was offered by Helen, as she talked about the presence of electrons in the salt bridge:

> Negative ions have electrons. Everything has electrons but negative ions have more than they need so there is a negative charge there. Once they are in the salt bridge

> they are not traveling freely but they travel attached to other substances to the other side of the circuit. They are hitching a ride with the sulfate and nitrate, to get over so they still have to travel through because they can't stop in a circuit.

The students' explanations about electron movement above were based on prior knowledge from lessons in junior high school science courses (Alberta Education, 2003). Dan indicated that he had learned that electrons move in complete circuits in grade 9 and both Helen and Ed referred to previous chemistry classes when explaining how ions were attracted to each other in the salt bridge. Another explanation based on prior knowledge was given by Colleen as she explained that the function of the inert electrolyte in the salt bridge was "to neutralize the charges on the moving ions", in the same way that a positive and negative ion combine to form "a neutral compound like the potassium nitrate in the salt bridge." Each of these students seemed to have actively constructed a logical framework for the functioning of a voltaic cell using information from current lessons and prior knowledge. The task of educators is to uncover the connections that students are making and help them confront their alternative conceptions so that scientifically accurate frameworks can be constructed.

Electrode Characteristics

Twenty-five percent of students believed that general descriptions of changes to electrodes during the operation of electrochemical cells were absolute. In the copper-zinc voltaic cell, the cathode did increase in mass as the copper was reduced and deposited on the electrode. Given enough time, much more than a typical laboratory activity, the zinc electrode would decrease in size as it oxidized. Because students had memorized these characteristics of electrodes, they believed that they saw it occur. In the voltaic cell, Mary observed, "You can see the copper (electrode) getting bigger, and over here the zinc (electrode) is definitely getting smaller". As Ken observed his electrolytic cell, he was asked, "What is happening at the carbon electrode" and he explained, "It is getting smaller. The anode always gets smaller". Gail deduced that her anode was decreasing in size in her electrolytic cell because as oxygen gas formed, the bubbles rose above the surface of the electrolyte and changed the appearance of her electrode. All of the voltaic cells used in laboratory activities or demonstrations observed in the classroom and over 50% of the diagrams in the Chemistry 30 textbook (*Nelson Chemistry*, 1993) contained two metal electrodes. Through exposure to predominantly one type of voltaic cell set-up, students may have been lead to apply general information rather than interpreting individual examples.

In question 10-2, the 30% of students who chose alternative B (see Figure 4-18 and Table 4-20), and 21% of students interviewed held the alternative conception that inert electrodes can be oxidized or reduced. For example, when observing his electrolytic cell, Liam explains, "Carbon solid is breaking down and releasing electrons so it is positively charged". Students had great difficulty with inert electrodes because carbon was not present on the redox table. However, when they were unable to locate carbon, three students did not change their problem-solving strategy but continued to look for it or attempted to incorporate it into their explanations. For example Andrew offered this explanation when observing his electrolytic cell.

[Andrew] “Carbon is deteriorating. Some gas is forming. Probably CO_2”

[Interviewer] “Why do you think it is CO_2?”

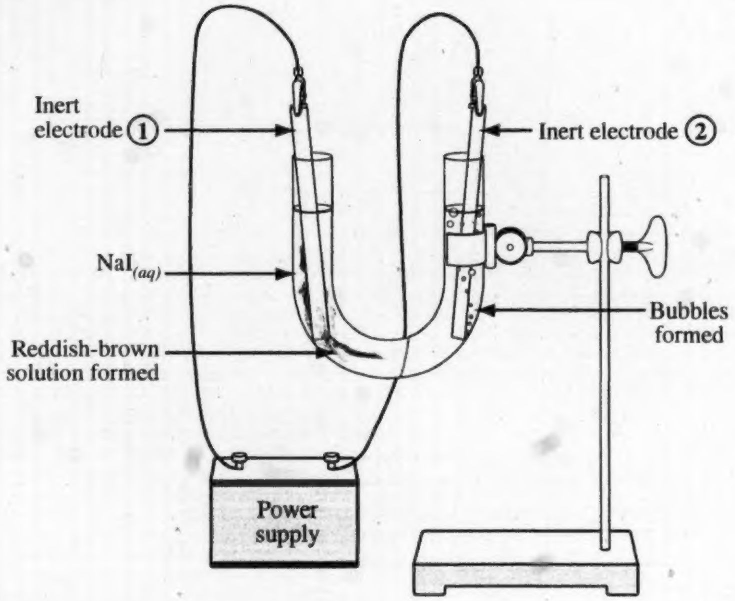
[Andrew] “There is oxygen in there in copper sulfate and it could bond with the carbon (in the electrode). We know that there is carbon so we can look for an equation in here with carbon in it”.

Andrew believed that carbon was participating in the reaction and found a way to explain it that made sense to him. When Sam observed precipitate formation on the copper electrode, he insisted that it was carbon forming, “The carbon is being reduced onto the electrode” and Gail insisted that carbon was a reducing agent but that it was just too weak to be included in the table.

Figure 4-18. Two tiered question 10 in the main study diagnostic instrument.

Use the following information to answer the next two questions.

A student set up the following electrochemical cell and allowed it to operate for a few minutes.


Inert electrode ①
Inert electrode ②
$NaI_{(aq)}$
Bubbles formed
Reddish-brown solution formed
Power supply

10-1. The gas formed near electrode 2 is **most likely**

- **A.** $I_{2(g)}$
- **B.** $Na_{(g)}$
- **C.** $O_{2(g)}$
- **D.** $H_{2(g)}$

10-2. Which of the following statements applies to the electrochemical cell in the diagram above?

- **A.** The same reaction occurs at each of the inert electrodes.
- **B.** The inert electrodes are oxidized and reduced in this cell.
- **C.** Water does not react during the electrolysis of aqueous solutions.
- **D.** The chemical reactions occur on the surface of the inert electrodes.

Table 4-20. Cross-tabulation analysis of two-tiered question 10 in the main study diagnostic instrument. Data is reported as percentage of students selecting the correct answer (n=87).

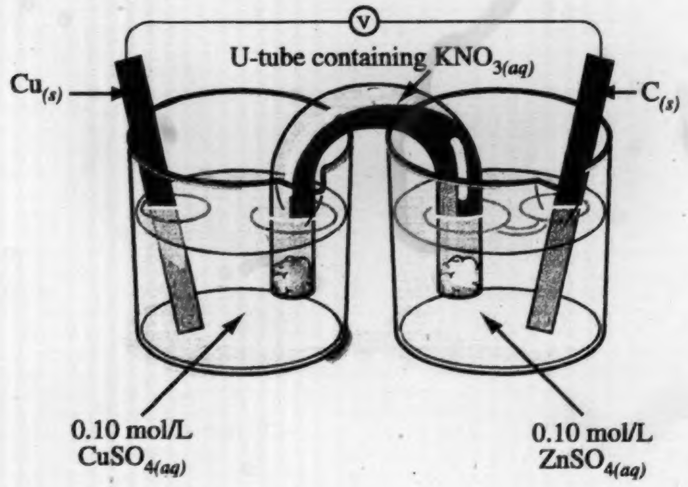
Conceptual Knowledge (10-2)		Procedural Knowledge (10-1)					
		A	B	C	*D	total	Alternative Conception
	A	0	0	0	2.3	2.3%	12d. In electrolytic cells with identical electrodes connected to the battery, the same reactions will occur at each electrode. (5)
	B	4.6	2.3	6.9	16.1	29.9%	13e. Inert electrodes can be oxidized or reduced. (5)
	C	1.1	1.1	0	1.1	3.3%	13a. Water does not react during the electrolysis of aqueous solutions. (2)
					50.6		
	total	11.4%	3.4%	14.9%	70.1%		

Note: (2) Garnett & Treagust, 1992b; (5) Ozkaya, 2002.

Students appeared to have developed a decision routine to use when solving routine voltaic cell problems but they did not seem have an alternative strategy to use for electrolytic cells and did not attempt to transfer knowledge to a different problem. Electrolytic cell problems can be solved by following the same five-step method used to predict reactions for voltaic cells. When inert electrodes are included in the problem, they are ignored when writing the equations because they do not contain a reactive chemical species. As Mr. Weber solved an electrolytic cell problem on the board for his students, he explained, "You use the same method to write the equation as we used for voltaic cells". Mr. Smyth expressed his frustration during the group interview, "We learned how to predict spontaneous reactions at the beginning of this unit by writing balanced equations using the redox table. But when I draw a voltaic cell on the board and ask the class what spontaneous reaction will occur, they don't transfer their knowledge from the equation lesson to the voltaic cells. They can't do the equations because the problem is different. I have to keep reminding them that the method is the same whenever we use the redox table but they don't make the connections by themselves". Electrochemical cells used in demonstrations and laboratory activities during classroom observation sessions had almost all contained two metal electrodes in their respective ionic solutions so that all species involved were found on the redox table used in class. Only one cell was demonstrated that contained an inert carbon electrode. Inert electrodes do appear in diagrams in the Chemistry 30 textbooks (e.g., 6 of the 26 diagrams in the electrochemistry unit in *Nelson Chemistry*, 1993) but students seemed to treat this as anomalous information and did not incorporate it into their problem-solving strategy.

To probe students' conceptual knowledge of inert electrodes, students were asked, "Can the copper or zinc electrode be replaced with an inert electrode?" Many students were skeptical about this question related to a non-routine voltaic cell. As Colleen explained, "Not unless we were electroplating in a voltaic cell, but I don't think we electroplate in voltaic cells". Over 70% of students chose to replace the copper electrode with an inert electrode (see Figure 4-19).

Figure 4-19. A representation of the copper-zinc voltaic cell that students assembled during the task-based interview in which students replaced the zinc electrode with an inert carbon electrode. This design will not operate because it does not contain a reducing agent to supply electrons for the cell from an oxidation reaction.



Each of these students had already written a half-reaction equation that represented the oxidation of zinc at the anode of the voltaic cell and correctly defined oxidation as a loss of electrons. Furthermore, they had explained that electrons travel from the anode to the cathode. When confronted with this novel problem, they were unable to transfer that knowledge and did not recognize that the metallic zinc was the source of electrons for this voltaic cell. The next attempt to solve this problem for nine of the students interviewed was to also replace the metallic copper electrode with an inert electrode so that the cell now contained two inert carbon electrodes. Only four students next proceeded to set up a cell in which only the metallic copper electrode was replaced by an inert electrode and only two of these students referred to their equations to find the source of electrons for the cell. Other students adjusted volumes, checked connections, or declared that it could not be done. When Peggy had succeeded using a means-ends problem-solving strategy to set up an operating cell, she was asked, "Can you explain what is happening in the cell".

[Peggy] "The electrons are being donated by the solution."

[Interviewer] "Why do we need the zinc solid?"

[Peggy] "They are just placed in the solution."

[Interviewer] "Can we do the same thing by taking the zinc out?"

[Peggy] "The current is flowing through the solution to the zinc in and out and if we take them out there is going to be nothing."

[Interviewer] "What is the purpose of having the electrodes here?"

[Peggy] "So that they (the electrons) can pass through for conducting."

Valerie explained her choice of an inert electrode at the anode: "carbon is the weakest reducing agent. It is not going to be stronger than anything. It is so weak that they don't even put it on the table." When asked why the zinc was present in the cell, Ed and Fran both said, "I don't know" and continued to search for carbon on the redox table. Each of these students successfully used procedural knowledge to predict the reactions with the redox table but did not seem to relate this knowledge to the underlying electrochemical concepts when confronted with a novel problem. Instead they attempted to fit a new problem into their existing decision routine and were baffled when the strategy did not work. Even though these students could correctly identify electron flow in the cell and write appropriate half-reaction equations, they had procedural knowledge of voltaic cells, but not conceptual knowledge and so could not transfer knowledge to a different context.

Everyday Meanings for Scientific Vocabulary

One source of alternative conceptions has been identified as the use of everyday meanings for scientific words (Sanger & Greenbowe, 1999). The everyday meanings of three terms, barrier, reversible, and polarity, seemed to limit students' conceptual knowledge in this study. The students' explanations of these terms are given below.

Barrier to Movement

A porous barrier is used in voltaic cells to prevent the mixing of the electrolytes in the two half-cells. Three students interpreted the term barrier to mean an obstacle to movement for ions and electrons. For example, Liam explained, "The porous barrier stops the electrons from directly moving. We don't see any blue (copper(II) ions) moving up through the salt bridge. The electrons move towards the mouth of the opening, as well the electrons in here (salt bridge) moving to either end. They can't actually cross the barrier". Patrick was asked, "Do the electrons travel through the electrolyte between the electrodes?" He replied, "There is a barrier. This (the porous cup) is stopping the two from touching each other. If you change the type of barrier, then the electrons can flow through (the electrolyte). I am not sure what it is called - filter wall or something like that – I saw it once" (a filter wall device was presented in a diagram during a lesson on types of voltaic cells). Both types of porous barrier, the porous cup and the salt bridge, were perceived by students to inhibit the movement of charged particles. This may limit their ability to develop conceptual knowledge of the movement of charged particles required for this electrical circuit.

Reversible Reactions

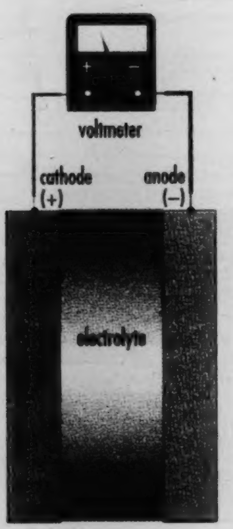
An application for electrochemical cells includes secondary or rechargeable batteries. All four teachers talked about both types of batteries during the classroom observations. Mr. Clarke and Ms. Maloney each had a collection of different types of batteries that they used in their lessons and students were asked to answer textbook questions related to the type batteries in popular use.

During the discharge of a battery, the chemical reactants are converted to products in the reaction. When the battery requires recharging, electricity is used to reverse the chemical reaction. Twenty one percent of students interviewed overgeneralized this contextualized explanation to mean that all reactions are reversible when electricity is added to an electrolytic cell. For example, when Colleen observed solid copper being electroplated onto the carbon electrode, rather than the copper electrode as she expected, she explained, "I must have switched around the (electrode) connections; the copper must be undergoing oxidation". Although she observed the copper being reduced, she believed that she could reverse the reactions, not just the location of the reactions, by switching the direction of the current.

Polarity

The concept of polarity in electrochemical cells caused a great deal of confusion for the students. The designation of positive and negative electrodes in chemistry and physics are opposite because they are based on different theories. The designation of (+) and (–) on electrodes in diagrams was stated as a fact in relation to charging batteries, but without a reason for the designation of the poles in the textbooks with which the students were familiar (e.g. *Science Focus* 9, 2002; *Addison-Wesley Chemistry*, 1993; *Nelson Chemistry*, 1993). In question 6-2 (see Figure 4-15), 29% of students selected alternatives A and B (see Table 4-18), and 30% of students interviewed held the alternative conception that anodes are negatively charged and cathodes are positively charged in voltaic cells. The two students who were taking classes in both chemistry and physics were unconcerned about the discrepancy and indicated that they had memorized the definitions specific to each subject. The polarity of the electrodes is represented by the (+) and (–) signs in Figure 4-20.

Figure 4-20. Diagram identifying polarity of electrodes in a voltaic cell



From: [1]*Nelson Chemistry* (1993) (p. 390)

---

[1] Jenkins et al. *Nelson Chemistry.*© 1993. Nelson Education Ltd. Reproduced by permission. www.cengage.com/permissions.

Redox Reactions

In question 4-2 (see Figure 4-21), 30% of students who selected alternative A (see Table 4-21) and 35% of students interviewed held the alternative conception that changes in charges of polyatomic species can be used to identify redox equations. However, only 11% of students chose a distractor related to this alternative conception in procedural knowledge question 4-1 that asked them to identify rules associated with oxidation numbers. Nancy identified an equation as a redox reaction "because it was the only one that had ionic charges with ammonium and hydroxide ions being created". Nineteen percent of students interviewed believed that a change in the number of oxygen atoms present in the reaction identified a redox reaction which supports another alternative conception. In question 4-2 (see Figure 4-21), 19.4% of students selected alternatives B or D (see Table 4-21), which were based on the alternative conception that redox reactions can be identified because the species that gains oxygen is oxidized and the one that loses oxygen is reduced.

Figure 4-21. Two-tiered question 4 in the main study diagnostic instrument

---

Use the following information to answer the next two questions.

1 $H_{2(g)} + Cl_{2(g)} \rightarrow 2\,HCl_{(g)}$

2 $SO_{3(g)} + H_2O_{(l)} \rightarrow H_2SO_{4(aq)}$

3 $NH_{3(aq)} + H_2O_{(l)} \rightarrow NH_4{}^{+}{}_{(aq)} + OH^{-}{}_{(aq)}$

4 $2\,NH_{3(g)} + \frac{1}{2}O_{2(g)} \rightarrow 2\,NO_{2(g)} + 3\,H_2O_{(g)}$

4-1. Which of the following is a correct statement about the oxidation state of an atom?

A. The oxidation number of oxygen in $O_{2(g)}$ is 0
B. The oxidation number of chlorine in $Cl_{2(g)}$ is -1
C. The oxidation number of nitrogen in $NH_4{}^{+}{}_{(aq)}$ is $+1$
D. The oxidation number of sulfur in $H_2SO_{4(aq)}$ is -2

4-2. Which of the equations above represent redox reactions?

A. 3 only
B. 4 only
C. 1 and 4
D. 2, 3, and 4

Table 4-21. Cross-tabulation analysis of two-tiered question 4 in the main study diagnostic instrument. Data is reported as percentage of students selecting the correct answer (n=87).

		Procedural Knowledge (4-1)					
Conceptual Knowledge (4-1)		*A	B	C	D	total	Alternative Conception
	A	18.4	3.4	4.6	3.4	29.8%	5a. In an equation, changes in charges of polyatomic species can be used to identify redox equations. (1)
	B	9.2	1.1	0	0	10.3%	6. In all chemical equations, the definitions of oxidation as the addition of oxygen and reduction as the removal of oxygen can be used to identify oxidation and reduction. (1)
	[redacted]	46.0	[redacted]	[redacted]	[redacted]	[redacted]	
	D	8.0	1.1	0	0	9.1%	6. In all chemical equations, the definitions of oxidation as the addition of oxygen and reduction as the removal of oxygen can be used to identify oxidation and reduction. (1)
	total	81.6%	7.9%	5.7%	4.5%		

Note: (1) Garnett & Treagust, 1992a.

In identifying redox reactions, some students believed that reactions could only be classified in one way. For example, combustion or formation reactions could not also be redox reactions, or if an acid were present, then it could only be an acid-base reaction. These types of reactions were used in other units of study in Chemistry 30 and were addressed by the students with procedural knowledge only. Facts were isolated to specific units, in the same way that many students do not transfer information from one subject to another. I observed Mr. Smyth helping a student solve a problem using the equation, $E^\circ_{\text{cell}} = E^\circ_{\text{cathode}} - E^\circ_{\text{anode}}$. The student knew the values for E°_{cell} and E°_{cathode} but did not know how to proceed. It was suggested that an X be used to replace the unknown E°_{anode}, but the student still could not complete the question. Mr. Smyth prompted, "What would you do in math class?" The student replied, "I would rearrange the formula for *X*", and doing this the student completed the question. Mr. Smyth talked about this attitude later, "Students don't seem to be able to make connections for themselves – they rely on me to do it. It is not just transferring skills from math class to chemistry. They don't do it in the same class either. The same method is used to write redox equations with the redox table whether it is just the equation or in a voltaic or electrolytic cell. But they don't see how the big picture is related – just the details. You know, can't see the forest for the trees." As an experienced problem solver in chemistry, Mr. Smyth sees the connectivity of the concepts. For a novice, however, making such relationships explicit requires conceptual knowledge, which is difficult to develop if the student approaches learning as the acquisition of bits of information.

The connections between different types of problems and the decision route for solving the problem must be made explicit for students. Mayer (2008) suggested that schema training, in which students "receive instruction and practice in recognizing problem types" (p. 175) can effectively improve students' problem-solving abilities. Fuchs, Fuchs, Thompson, Al Otaiba, Yen, Yang, et al. (2004, as cited in Mayer 2008), reported that math students showed significant improvement in problem solving when they received instruction not only on how to solve a problem, but also how to recognize different types of problems. Quilici and Mayer (2002, as cited in Mayer 2008) obtained similar results with students studying statistics in college. Instruction for redox reactions, voltaic cells, and electrolytic cells occurred in separate lessons during the classes observed in this study and no attempt was made either in group discussions or in assignments to explicitly identify the similarities and differences between the decision routines that students developed during these lessons.

Redox Table

For question 1-2 (see Figure 4-22), 16% of students selected alternative D based on the alternative conception that the reduction potential for the standard hydrogen half-cell is not arbitrary but based on the chemistry of $H^+_{(aq)}$ and $H_{2(g)}$. Although students recognized that the cell potentials observed for their electrochemical cells were the difference between the potentials of two different half-cells, 16% of students interviewed believed that if the hydrogen half-cell was attached to a voltmeter, the measured quantity of 0 volts would be produced. They did not have conceptual knowledge of the relative nature of the redox table, even though they could use it for procedural knowledge questions.

The alternative conception that half-cell potentials are absolute in nature and can be used to predict the spontaneity of the half-cells was used to develop alternatives in two questions in the main study diagnostic instrument. In question 1-2 (see Figure 4-22), 32.1% of students selected alternative B and 2.3% of student selected alternative C (see Table 4-22). In question 2-2 (see Figure 4-8), 19.4% of students selected alternative A (see Table 4-5). In the interviews, however, only 10% of students were found to hold this alternative conception. For example, Nancy explained, "the copper half-reaction is spontaneous because the number in the table is positive". Although students had memorized that the hydrogen half-cell was the reference for the redox table, none of the students interviewed could explain why a standard reference half-cell was needed or why hydrogen was chosen. The term reference half-cell was used during classroom instruction, in the textbook and in assigned work. Thus students should have had procedural knowledge of the term and could solve problems that used it but they did not have conceptual knowledge of a reference half cell or how it formed the basis for the reference table used in this unit of study.

Figure 4-22. Two tiered question 1 in the main study diagnostic instrument

---

1-1. The half-reaction to which all other half-cell reduction potentials are compared is

A. $Li^{+}{}_{(aq)} + e^{-} \rightarrow Li_{(s)}$
B. $F_{2(g)} + 2\,e^{-} \rightarrow 2\,F^{-}{}_{(aq)}$
C. $2\,H^{+}{}_{(aq)} + 2\,e^{-} \rightarrow H_{2(g)}$
D. $Au^{3+}{}_{(aq)} + 3\,e^{-} \rightarrow Au_{(s)}$

1-2. Which of the following statements explains why a standard half-cell is used?

A. The designation of 0 V for the standard half-cell is arbitrary.
B. The hydrogen half-cell is the only reduction half-reaction that produces 0 V.
C. All half-reactions that are listed above the standard half-reaction on a table of reduction half-reactions will be spontaneous.
D. The designation of the standard half-cell is based on the chemistry of the components that make up the half-cell.

Table 4-22. Cross-tabulation analysis of two-tiered question 1 in the main study diagnostic instrument. Data is reported as percentage of students selecting the correct answer (n=87)

	Procedural Knowledge (1-1)						
Conceptual Knowledge (1-1)		A	B	*C	D	total	Alternative Conception
				48.3			
	B	1.1	0	31.0	0	32.1%	9c. Half-cell potentials are absolute in nature and can be used to predict the spontaneity of the half-cells. (5)
	C	0	0	2.3	0	2.3%	9c. Half-cell potentials are absolute in nature and can be used to predict the spontaneity of the half-cells. (5)
	D	0	1.1	14.9	0	16.0%	9a. The designation of the E^o for the H_2/H^+ (1 M) standard half-cell is not arbitrary but based on the chemistry of $H^+_{(aq)}$ and $H_{2\,(g)}$. (2)
	total	1.1%	1.1%	96.5%	1.1%		

(2) Garnett & Treagust, 1992b; (5) Ozkaya, 2002.

Additional Alternative Conceptions Identified During Student Interviews

Alternative conceptions that have not previously been reported in the literature were identified in the interviews with students related to the following electrochemical concepts:

- electric circuits and current
- voltaic cells
- electrolytic cells
- electrical neutrality

These new alternative conceptions are reported in Table 4-23 and have also been compiled in Appendix D with those previously reported in the literature by Garnett and

Treagust, 1992a; 1992b; Ogude and Bradley, 1994; Sanger and Greenbowe, 1997a; 1997b; and Ozkaya, 2002.

Electric Circuits and Current

Twenty-one percent of students interviewed held the alternative conception that electrons were transported through the electrolyte by negative ions (1c, see Table 4-23). Ed explains, "It is the sulfate negatives that have the electrons. They are going over there (towards the anode)". The charge of two negative on the sulfate ion was interpreted as meaning two free electrons which were transported to the anode to provide a continuous electrical circuit.

Twenty one percent of students interviewed believed that the electrochemical cells operated because of electron repulsion, by forcing the electrons from the anode into the wire (2j). Olivia explains that electrons move "because they are pushed through (the wire) by the other electrons; they are repelled.

Voltaic Cells

Fourteen percent of student interviewed believed that the movement of anions was caused by the repulsion of like charges (13i). Anions move through the salt bridge because when the electrons come into the solution at the cathode, negatively charged particles in the electrolyte are repelled and move to an area of lower negative concentration in the salt bridge. Fran explained, "Anions move because this solution (electrolyte at the cathode) has more negatives because of the electrons coming in so then they (the anions) would repel and go the other way".

Electrolytic Cells

Students had more difficulty learning electrolytic cells and had some surprising interpretations. Twenty one percent of students interviewed believed that only one reaction occurred in an electrolytic cell (13h). After identifying that carbon would function as the anode in his electrolytic cell Ed explains, "I am pretty positive that there is no second reaction, just this one (the copper reduction half-reaction)". Dan agreed with this alternative conception stating, "there is just reduction here, there is no oxidation happening".

Sixteen percent of students interviewed believed that it was not necessary for ions to move when only one container was used in an electrolytic cell (13i). Twenty one percent of students believed that anions and electrons moved to complete the circuit but it was not necessary for cations to move in one container (13j). Thirty two percent of students believed that electrons flow through the wire only in a voltaic cell, but because of the absence of a salt bridge, the electrons continued through the electrolyte in an electrolytic cell (13k).

Electrical Neutrality

Electrical neutrality was interpreted in three alternative ways by students in this study. Dan did not believe that anions were moving towards the anode because of the loss of electrons from that electrode but rather that "sulfate ions move to the anode to match up with more zinc ions to neutralize the electrical charges because electrons repel each other" (18a). Jayne believed that the function of the salt bridge was to keep the cell electrically neutral because "the electrons are being taken away here (at the cathode) and the cell adds more negative ions to the anode side from the salt bridge to balance the charges" (18b). Colleen believed that the "inert substance in the salt bridge is used to neutralize the cell" (18c) but she wasn't sure if it would still be necessary if a porous cup was used. Sixteen percent of students believed that ions move in opposite directions to equalize concentration of charges (18d). For example, Fran believed that there were hydrogen ions in her solution and explained that they move towards "the anode because copper is already going towards the cathode. They are going in opposite directions because if they are all going to one, there is nothing at the other one".

Table 4-23. Alternative conceptions identified in this study

1c. Electrons move through the electrolytes by being transported by negative ions in solution

2j. Electron repulsion in the anode forces electrons to move from the anode into the connecting wires

2k. Anions move because of repulsion by anions

10g. Electrons can flow through the electrolyte in the absence of a salt bridge

11c. The cathode is negatively charged and because of this it repels anions causing them to move away from the cathode and towards the anode

13h. Only one half-reaction occurs in an electrolytic cell because it occurs in one container

13i. Ions do not move in an electrolytic cell because it occurs in one container

13j. Only electrons and negatively charged ions constitute a flow of current in an electrolytic cell

13k. Electrons flow through the electrolyte in an electrolytic cell because the salt bridge is absent

13l. Spontaneous reactions can be reversed by changing the direction of electron flow

18c. The cell is electrically neutral because anions move towards the anode and react with cations produced during oxidation

18d. As electrons are removed in the reduction reaction at the cathode, the negative charges are replaced by anions supplied from the salt bridge

18e. The inert substance in the salt bridge neutralizes the electrolytes in the cell

18f. Cations and anions move in opposite directions to equalize the concentration of charges in the cell

18g. Cations move in both directions in the salt bridge to equalize the concentration of positive charges between the two half-cells

Confronting Alternative Conceptions

By talking aloud about a process, either individually or in groups, students may be able to recognize and confront their alternative conceptions and meaningfully learn the concepts. In this study, some students confronted their alternative conceptions when their observations did not correspond with their predictions. For example, Fran was explaining the operation of her electrolytic cell,

[Interviewer] "Do electrons pass through the electrolyte?"

[Fran] "No I don't think so."

[Interviewer] "Does anything pass through the electrolyte?"

[Fran] "No because the water just changes. Hey wouldn't some of the electrons come from the water? So they (the electrons) don't come from the carbon (searching on the redox table)"

[Interviewer] "Why did you think the electrons came from the carbon?"

[Fran] "I just always thought that they started in one electrode and went to the other electrode and then they are done."

[Interviewer] "Do they actually start in the electrode?"

[Fran] "There are some in there but that is not where the flow starts. It must start from the water when it reacts and then it loses electrons and it goes into the anode."

Gail was also able to recognize discrepancies between what she was saying and her observations as shown by her explanation of electron movement in her voltaic cell.

> The electrons are in the salt bridge too. They should be there. Yes they are there because electrons can move in an electrolyte. No, they shouldn't be there because you

> are using the electrons to make the copper solid. So the electrons only travel through the wire and not through the electrolyte because they are used up at the cathode.

In their study with eighth-graders, Chi et al. (1994) observed that students that were prompted to generate self-explanations while reading a biology passage improved their ability to construct knowledge inferences and to integrate new knowledge with prior knowledge. In the student interviews related to the main study diagnostic instrument, student answers were recorded and then removed from the instrument prior to the interview. This was done so that if an alternative conception had been confronted during the task-based interview, the student's explanation of their choice might reveal a change in their thinking about the problem. Indeed, students identified over 60% of their incorrect choices during their explanations, frequently explaining why their answer was being changed as a result of the task-based interview. This is in agreement with Siegler's (2002) finding that prompting students to explain both correct and incorrect solutions led to greater procedural flexibility than only explaining correct solutions. In this study, students were asked to self-explain both correct and incorrect answers to maximize the effectiveness of the explanation condition. The requirement to explain their processes and decisions can encourage students to recognize when procedural knowledge is inadequate and promote more cognitive engagement with the task.

Students construct their own knowledge personally (personal constructivism) and during social engagement (social constructivism). Vygotsky (1962) believed that as children learn to use new words they internalize their meanings. He believed that the process of cultural development of word meaning occurred first on the social level, and then on the individual level with word meaning generalization. As children begin to use and internalize new words in the presence of a knowledgeable other person, they often find themselves in the zone of proximal development (ZPD), that place for learning located somewhere between the child's present and potential understanding (Vygotsky, 1978). In the ZPD, children are able to do in collaboration today with a knowledgeable person what they will be able to do independently tomorrow. As Bruner (1986, p. 132) said, it is this "loan of consciousness" that gets children through the ZPD. He suggested that by building the student's knowledge base and by taking the student from the familiar to the unfamiliar, a teacher can assist in furthering learning by providing accurate information to assimilate with present knowledge. By carefully involving students in appropriate activities, the teacher can create the ZPD so that the student is supported by both their classmates and their teacher.

The importance of social engagement was apparent during some of the interviews. Fran was able to identify and confront her alternative conception about electron movement as she self-explained during her interview. Activities in which students must explain their problem-solving strategies, not merely identifying their decision routes, and communicate their decisions and ideas to each other and their teacher could promote meaningful learning of the processes under study.

Bransford et al. (1999) called identifiable pieces of students' knowledge "facets," a convenient unit of thought, a piece of knowledge, or a strategy seemingly used by the student in addressing a particular situation. Facets may relate to conceptual knowledge, to procedural knowledge, or be generic. By listening to student explanations and by identifying students' facets, educators can determine what cues students use in different contexts, how they use these cues in reasoning, and then use this information to devise instructional strategies that would increase meaningful learning and understanding.

Summary

For more familiar problems, those involving routine voltaic cells, students seemed to have developed some conceptual knowledge. Many students used a working-forwards problem-solving strategy, and over half of the students interviewed used two or three levels of representation when predicting or explaining. For questions involving voltaic cells in the main study diagnostic instrument, students scored higher on both procedural and conceptual knowledge questions and fewer students held alternative conceptions related to the operation of these cells.

For less familiar problems, those involving non-routine voltaic cells and electrolytic cells, students preferred to approach problem-solving with procedural knowledge. They generally scored higher on procedural knowledge than conceptual knowledge questions in the main study diagnostic instrument. Students used decision routines that involved memorized formulas and procedures for both quantitative and qualitative problems. For routine problems that were familiar to them, a working-forwards problem-solving strategy was employed. However, for non-routine cells, students could not transfer their decision routines to novel problems because of limited conceptual knowledge of the underlying chemistry concepts. Most students used only one level of representation of knowledge when explaining the operation of these electrochemical cells.

Students experiencing difficulty understanding electrochemistry did not see how chemistry concepts were related because they seemed to approach the topic by learning discrete pieces of information and then applying the pieces in isolation when solving problems. For example, many students would make predictions using the symbolic level of representations but would not refer to this information to help them explain the operation of the cell that they had constructed. Furthermore, some explanations of cells revealed alternative conceptions that contradicted predictions or observations that had been made as part of the same activity which highlighted the lack of connectivity of the chemical concepts for students related to electrochemical cells.

It may be that by posing problems related only to the discrete categories used in the framework of analysis in this study, (types of knowledge used in problem solving, levels of representation of knowledge, and alternative conceptions), we may be promoting the compartmentalization of the students' information rather than encouraging them to strive to understand the complexity of electrochemical cells.

CHAPTER V

CONCLUSIONS AND SUGGESTIONS FOR TEACHING

Overview of the Study

The aim of this study was to look at students' understandings at the end of a unit on electrochemistry. The three categories used in the framework of analysis for this study were types of knowledge used for problem-solving, levels of representation of knowledge in chemistry, and alternative conceptions. Although individually each of the three categories had been reported in previous studies, the contribution of this study is that the inter-relationships among these three categories (see Figure 4-1, p. 106) were found to limit student learning and understanding in electrochemistry. Students who had developed conceptual knowledge of the relationship among electrochemistry concepts used a working-forwards problem solving strategy, offered explanations that included two or three of the levels of representation of knowledge and held fewer alternative conceptions. However, evidence of this type of knowledge was only apparent with routine voltaic cells. For non-routine voltaic cells and electrolytic cells, students relied on procedural knowledge to solve problems, struggled to make connections between the levels of representation and held a greater number of alternative conceptions.

Both quantitative and qualitative decision routines based on procedural knowledge were used to solve problems without conceptual knowledge of the underlying chemical concepts. Using a decision routine, students used a working-forwards, problem-solving strategy to successfully solve routine problems using the individual levels of representation of knowledge, but they had limited ability to transfer among the three levels of representation when solving problems. They could successfully solve familiar problems (e.g. routine voltaic cell), but could not transfer their knowledge when the context of the problem changed. Without learning the relationship between the symbolic language of chemistry, and the particulate and macroscopic aspects of chemical reactions, their problem-solving strategies became focused on memorized procedures, vocabulary and acronyms. Although this learning strategy did seem to enable students to be successful on traditional paper-and-pencil assessment methods, it appeared to involve the acquisition of discrete pieces of disconnected information, relied on procedural knowledge, and so was insufficient for meaningful learning.

Problems involving non-routine voltaic, those that did not contain two metal electrodes and their matching electrolytes, and electrolytic cells were very challenging for students in this study. Decision routines were only applied to familiar problem-types and without an entry into non-routine problems, students unsuccessfully used a means-ends problem-solving strategy for such novel problems. Furthermore, they did not attempt to relate the three levels of representation in their explanations even when guided to do so and there was evidence of alternative conceptions in their explanations.

The main source of alternative conceptions in this study seemed to be the overgeneralization of theory related to the particulate level of representation in chemistry, such as bonding theory or electrostatic attraction, as students tried to make sense of the abstract nature of atoms, molecules, electrons, and ions. These overgeneralizations were not unique to electrochemistry, but this serves to highlight that difficulties arise for students when they are required to develop mental models for abstract concepts in science, particularly if their problem-solving strategies are limited to the use of procedural knowledge.

In the following sections, each of the three categories used in the framework of analysis will be discussed. Students who had difficulty understanding electrochemistry in this study experienced problems with each of the three categories. However, addressing issues in one of the categories may not be enough to promote meaningful learning if done without addressing the other two categories as well. It is likely that the suggestions made here for teaching have already been made elsewhere. In the context of this study, they are made specifically for the teaching of electrochemistry and attempt to present ideas that might help students to see the relatedness between the three categories used in the framework of analysis in this research.

Category I: Types of Knowledge Used in Problem Solving

The type of knowledge used to solve electrochemistry problems by students was predominantly procedural knowledge. They were able to use definitions, acronyms, and identifiable patterns to make predictions and give explanations about electrochemical cells, but they did not have conceptual knowledge of the underlying chemistry concepts. Strategies that allowed students to follow a procedure such as manipulating equations and formulas or following steps in a process, were insufficient when it came to solving novel problems that required conceptual knowledge. Students may have experienced limited development of conceptual knowledge of electrochemical cells because although they knew individual concepts such as identifying a reduction reaction and calculating a cell potential, they may not have developed a context within which the complex process operated.

The students and teachers in this study were at different places along the novice-expert continuum with respect to problem-solving. This continuum reflects the experience that each group would have in relation to the types of problems being solved. Students had more experience with routine voltaic cells and so could be considered further along on this continuum when working with such problems. For problems with which they were less familiar, such as non-routine voltaic cells and electrolytic cells, their problem-strategies were closer to the novice end of the continuum (see Figure 5-1). Although chemistry teachers were experienced problem solvers, few would have encountered the problem-solving rigour of professional electrochemists and so teachers are represented close to, but not at, the expert end of the continuum.

Figure 5-1. The relationship between the novice-expert continuum and the category of problem-solver, types of problems, and problem-solving strategy

Novice-Expert Continuum

Novice ⟶ **Expert**

Category of Problem-Solver

Students ....Chemistry Teachers ....Professionals

Types of Problems in this Study

Electrolytic.............Non-routine.........Routine..
Cell (novel)   Voltaic Cell   Voltaic Cell

Novice v Experts Problem-Solving Strategies

Procedural Knowledge... Conceptual Knowledge
Decision routines memorized....................................Decision routines developed
Decontextualized knowledge.......................................Contextualized knowledge
Limited transfer of knowledge...............................Transfer between problem types
Limited retention of knowledge.................................Good retention of knowledge
Rigid problem-solving strategies......................Adaptable problem-solving strategies

Mayer (2003) proposed that word problems require four iterative steps: translating, building a mental model of the problem, planning, and executing. In this study, students had the most difficulty with the translating and planning phases as represented by their use of one decision routine to solve routine voltaic cell problems, but lacking a strategy when the context of the question changed to non-routine voltaic cells or electrolytic cells. This may have resulted because most instruction and problem-solving practice observed in this study focused on executing problems. One might argue that teaching students to use a systematic approach to problem solving promotes a procedural behavior because students might not find it necessary to make the conceptual linkage to achieve a level of success in problem solving that is expected of them by their teachers. The great debate in mathematics education has involved the dichotomy between helping students get the right answer using procedural knowledge that emphasizes a skills approach, and helping students meaningfully learn what they are doing using a conceptual knowledge approach that emphasizes understanding. The former goal may be efficiently achieved by emphasizing procedural knowledge using traditional learning strategies; however, a different strategy may be required if the goal is to promote conceptual knowledge. Students who used decision routines based on procedural knowledge could master problems requiring mimicking, regurgitation, and short-term memorization. They could not master problems; however, requiring comparison and explanation for non-routine or novel problems. Such problems may require long-term cognitive development where knowledge is genuinely stored, structured, and networked. Learners with conceptual knowledge are capable of probing information and explaining the underlying reasons for their observations and conclusions regarding scientific phenomena. This happens because conceptual learners evolve over a period of time from their learning experiences; their understanding is a manifestation of collected knowledge, not immediate knowledge. It would seem apparent then that more time is needed to allow students to develop conceptual knowledge but different assessment strategies are also needed to determine if or when such knowledge has been acquired by students.

It has been proposed that the human cognitive system deals with complexity by incrementally building up complex decision routines or schemas in long-term memory. The elements that go to make up these schemas must first be processed in working memory but working memory is structured to only process a very small number of those elements at a time. It can only process a large number of elements once they have been incrementally structured, or chunked, into usable patterns, and then stored in long-term memory (Sweller, 2006). Learning may involve alterations in long-term memory by the acquisition of large numbers of domain-specific decision routines. Instructional material should be structured to reduce working memory load when dealing with complex, high element interactivity material presented to novices. The learning of individual chunks of information, such as learning to write redox equations before learning to apply them to voltaic cells, is an example of teaching elements of information.

Pollack, Chandler, and Sweller (2002) suggested that material must initially be learned as isolated elements, ignoring the interactions between them. By ignoring interactions between elements, learning the material is compromised, but working memory can handle the isolated elements. Once they have been learned, interactions between elements can further learning resulting in full understanding. By subsequently presenting the material with full emphasis on understanding the interacting elements, learning and understanding are facilitated. For example, students could come to appreciate how a redox table is constructed using experiments involving spontaneous and nonspontaneous reactions as one element. Using the redox table to predict spontaneous reactions would be a separate element. Although the students had knowledge of these two elements, most students did not seem to see the connectivity between them. Such relationships must be made explicit for students.

While problem solving using decision routines indicates how a problem should be solved, searching for ways to solve a problem is a different cognitive activity to learning which method will best lead to a solution. As a consequence, problem solving with a means-ends strategy could interfere with learning (Sweller, 1988) because the student may not have a method to successfully approach even routine problems. For quantitative problems and for routine voltaic cells in this study, students used a working-forwards strategy by selecting and applying a decision routine to solve the problem. When a mathematical formula was forgotten or for problems involving non-routine and electrolytic cells, students used a means-ends strategy, attempting to solve the problem by trial-and-error because their procedural knowledge did not seem to be supported by sufficient conceptual knowledge to allow them flexibility in their problem solving strategies. Students may have acquired two decision routines. A quantitative decision routine was used for problems requiring mathematical manipulations, and a qualitative decision routine was applied to problems involving electrochemical cells.

Quantitative Decision Routines

The decision routine used for quantitative problems involved the application of two formulas to solve for the amount of a substance in moles, $n = \frac{m}{M}$ for a chemical species and $n = \frac{It}{F}$ for electrons. If students could not remember the formula, then they could not apply this decision routine and were unable to proceed with the mathematical problem. The method required to convert between the chemical species and the electrons requires a half-reaction equation that represents the relationship between the two, in the form of a ratio. Twelve of the nineteen students who had correctly chosen a half-reaction equation in the first tier of a question in the main study diagnostic instrument, failed to apply this information in the calculation in the second tier of the question. Recognizing that they did not learn how the two elements were related, students explained that they had memorized another equation which served to combine the two equations and included the valence of the chemical species instead of a ratio, $m = \frac{ItM}{FV}$. Unfortunately, students who could not recall the formula, or who did not remember how to determine the value for V (e.g. using the charge on a cation), were unable to proceed with this type of problem. Since their decision routine was based on procedural knowledge, no alternative strategy was available to use because they did not have conceptual knowledge about how the elements of the problem were related to each other.

Students identified a preference for quantitative problems because they felt they had a better chance to be successful when using with a memorized formula. The teachers acknowledged this preference, and although some different problem-solving strategies were introduced at the beginning of the unit, the strategy in all the class problem-solving sessions that were observed had reverted primarily to the use of formulas.

Qualitative Decision Routines

Students had developed a decision routine to solve problems with routine voltaic cells that contained two metals and their matching ionic solutions. The generalized decision routine was comprised of the following steps.

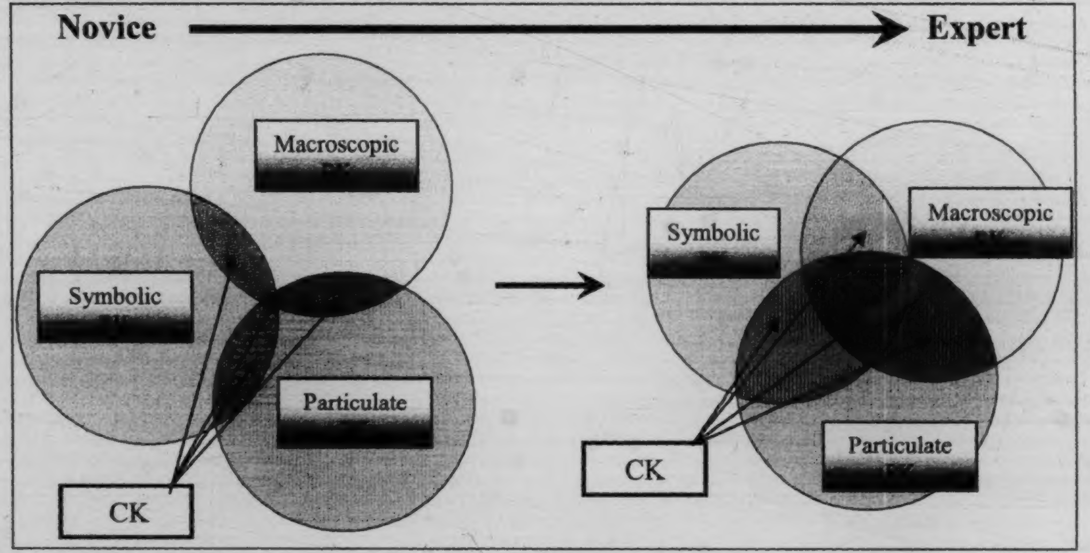
1. With the redox table, use a memorized pattern and acronyms to identify the cathode and the anode
2. Assemble the voltaic cell with the metals in their matching ionic solutions
3. Use memorized acronyms and patterns to describe the motion of electrons and ions

The decision routine was successfully applied to all routine voltaic cells, the type that were most commonly used in examples during lessons, demonstrations, laboratory activities, worksheet and textbook assignments, textbook diagrams, and during assessment on quizzes and tests. When the context of the problem changed to a non-routine voltaic cell or an electrolytic cell, students either did not attempt to apply their decision routine, or applied it unsuccessfully.

Category II: Levels of Representation of Knowledge in Chemistry

Students had developed procedural knowledge of each of the three levels of representation of knowledge in chemistry for routine voltaic cells. They were proficient at writing equations at the symbolic level, setting up cells and making observations at the macroscopic level, and identifying the direction of movement of anions, cations and electrons at the particulate level. They seemed to have limited ability to transfer between the levels, a process involving conceptual knowledge in chemistry. De Jong and van Driel (2001) postulated that the symbolic level of representation was the interface between the levels (see Figure 2-2); however, in this study, the relationship among them was more complex (see Figure 4-1). Students had good procedural knowledge of each of the three levels, but seemed to use them independently. For example, some students who had written a half-reaction equation representing the production of solid copper at the cathode in an electrolytic cell identified the solid forming there as carbon. They had procedural knowledge of symbolic and macroscopic levels of representation of knowledge but they did not seem to have the conceptual knowledge required to understand the relationship between the two. Some students included more than one level in an explanation; however, this did not seem to be intuitive for most students. Students were exposed to multiple presentation methods. One school used laboratory demonstrations and computer animations. The other school used laboratory activities and still diagrams. However, the relationship between the levels of representation was not made explicit to the students during the lessons observed. Teachers, with their increased problem-solving experience may more naturally see the relationship among the three levels of representation of knowledge thus reflecting a greater degree of conceptual knowledge Novices, less experienced problem solvers, appeared to need assistance in making the implicit explicit in their knowledge structures and seemed to depend on a greater degree of procedural knowledge (see Figure 5-2).

Figure 5-2. Relationship among the levels of representation of knowledge in chemistry showing increasing conceptual knowledge on the continuum from novice to expert.



Note: PK- procedural knowledge; CK- conceptual knowledge

Imprecise or everyday language seemed to lead some students, who were relying on procedural knowledge, to ignore their representations of knowledge at the symbolic and macroscopic levels. The use of terms like reversible reactions in rechargeable batteries, an example of an electrolytic cell, led students to overgeneralize the term to include the reversal of reactions, rather than reversal of the flow of electricity. For example, a student had predicted the reduction of copper ions to solid copper at the cathode in an electrolytic cell. When the solid precipitate formed in the opposite half-cell to the one predicted the student assumed that because the electricity was moving in the opposite direction, then the reaction occurring must be the oxidation of copper, the opposite of reduction. When words with everyday meanings are used in science classes, care must be taken during instruction to probe student understanding of the words to determine if they align with the intended meanings.

Category III: Alternative Conceptions

A large inventory of alternative conceptions in electrochemistry has been documented over the past 15 years. A number of these alternative conceptions were identified through the use of the diagnostic instrument designed for this study, as were a number of new ones during student interviews. Additionally, a few alternative conceptions that were identified by the main study diagnostic instrument were found to be the result of students interpreting the questions in an unexpected manner. The alternative conceptions held by students seemed to be the result of over-generalizing information from previous chemistry and physics classes, in addition to the use of everyday meanings for scientific words, predominantly related to the particulate level of representation of knowledge.

Additional Alternative Conceptions Identified

Alternative conceptions that were previously unreported in the literature were identified in this study relating to three areas: electron movement, electrical neutrality, and reactions in voltaic and electrolytic cells. These previously unidentified alternative conceptions held by students in this study are reported in the table 5-1.

Table 5-1. Alternative conceptions identified in this study that were previously unreported in the literature.

Electron Movement

- electrons are transported through the electrolyte by negative ions
- electrochemical cells operate because electrons are forced by repulsion of like charges from the anode into the wire
- anions move because they are repelled by the negatively charge electrons

Electrical Neutrality

- anions move towards the anode to neutralize the cations from the oxidation reaction
- the salt bridge provides anions to equalize the concentration of negative charges

between the two half-cells

- the inert substance in the salt bridge neutralizes the cell
- positive ions move in both directions in the salt bridge to equalize the concentration of positive charges between the two half-cells
- cations and anions move in opposite directions to equalize the concentration of charges in the cell

Voltaic Cells

- electrons can flow through the electrolyte in the absence of a salt bridge
- the cathode is negatively charged and because of this it repels anions causing them to move away from the cathode and towards the anode

Electrolytic Cells

- only one half-reaction occurs in electrolytic cells
- ions do not need to move to maintain electrical neutrality if the cell is in one container
- only anions and electrons move to complete the circuit
- in the absence of a salt bridge, electrons flow through the electrolyte
- spontaneous reactions can be reversed by changing the direction of electron flow

Sources of Alternative Conceptions

In an attempt to make sense of the particulate level of representation in electrochemical cells, students seemed to overgeneralize prior knowledge of electrostatics and magnetism from previous science classes. The idea that charged particles move because like charges repel each other and unlike charges are attracted, was an adequate explanation for magnets in grade 6 and ionic compounds in grades 9 and 10. In the absence of conceptual knowledge about electrochemical cells, these facts became the basis for student explanations at the particulate level of representation of knowledge.

Overgeneralization of the terms neutral, inert, complete circuit, and reversible also seemed to cause problems for students. Students appeared to apply the principle of diffusion, which was learned in grade 10, to electrochemical cells. Cells were considered neutral when charged particles moved until there were equal concentrations in both half-cells. An inert substance was considered neutral and was given the property of a neutralizing agent, a connection that could have been related to acids or bases from grade 11 chemistry. In chemistry, inert means unreactive, so the replacement of a metal electrode with an inert one seemed to logically mean that there would be one less reaction occurring in an electrochemical cell. When studying circuits in grade 9, electricity was produced when electrons completed a circuit and this was reinforced by everyday experiences with household electricity. Writing a reduction half-reaction indicating that electrons are consumed in one part of the circuit does not present a conceptual conflict when students possess an adequate working theory. Students were familiar with rechargeable batteries and had learned that putting them in a battery charger reverses the reactions and recovers the reactants so that the battery can once again operate. In this study, students seemed to apply that information to electrolytic cells predicting that a spontaneous reaction could be reversed by switching the direction of current flow.

Promoting Conceptual Knowledge Development

In a study of students' learning of chemical reactions, Kwen (1996) concluded that across a group of events that were perceived to be similar, students applied scientific or alternative frameworks consistently but what appeared to be lacking was the scientists' recognition of the underlying conceptual model. Students in his study tended to use different alternative conceptions for the same aspect, or the same concept on different events, which suggests that students did not understand the idea of scientific reasoning to explain generality of events. This may be due in part to the lack of understanding among students of the nature of science and its goals, and their tendency to transfer everyday goals and everyday ways of thinking into the domain of science. Because everyday thinking may only require adequate but not maximal generality and consistency, students may have developed a tendency to view doing science as the same, even if the ideas were inconsistent with the phenomena under study. Treagust et al. (2003) concluded that familiarity with the purpose of each level of representation can enhance a learner's learning and ability to explain a concept. Consequently, the development of students' knowledge from a procedural to a conceptual level could be aided by linking their experiences of the behavior of chemicals at the macroscopic level with the symbolic and particulate levels of representation.

Use of the Diagnostic Instrument

Teachers may benefit from the availability of an easy-to-use means of identifying the type of knowledge on which students rely during problem solving and the alternative conceptions held by students since knowing these could aid planning of lesson sequences. If it is known which alternative conceptions occur, teachers could reflect on how to respond to students' incorrect answers and plan strategies to challenge their thinking. The diagnostic instrument used in this study may facilitate the convenient identification of students' conceptions and alternative conceptions and the congruence between their procedural and conceptual knowledge of electrochemical concepts. However, the instrument designed for this study was not intended for use as summative assessment. It was my intention to develop a tool that could help teachers to navigate the myriad alternative conceptions identified in electrochemistry and serve as a starting point for conversations with students about their current conceptions. Students should be encouraged to think and verbalize their thoughts because if they are required to explain their ideas while participating in a lesson or activity which has been chosen to confront alternative conceptions known to be held by students in a class, then these alternative conceptions can be challenged in the context of adequate problem-solving strategies. When students' ideas are valued sufficiently that they become part of classroom discourse, a proliferation of ideas will suggest the need to choose between them, with some gaining greater acceptance than others. There is a paradox here because, while students' ideas are valued, the status of some would be reduced. The paradox disappears; however, in the recognition that, in moving from ideas to the basis for choosing between ideas, the nature of the discourse has changed significantly.

Recommendations for Teaching

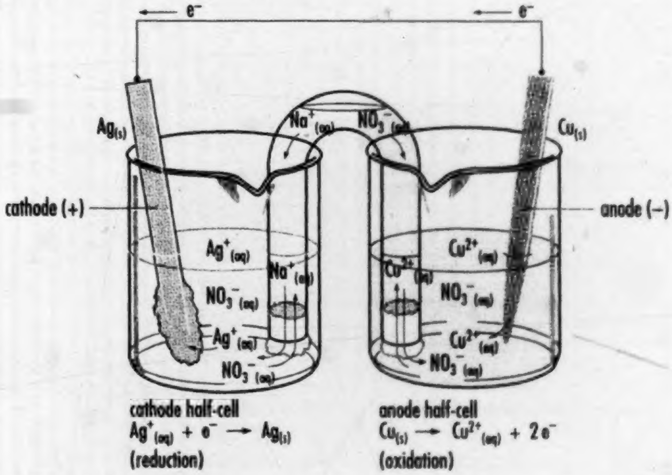
For conceptual knowledge to develop, students should be exposed to a wide variety of problem types and contexts. Problems could be posed that would identify students' current conceptions, both those that align with scientific canon and alternative explanations. The solution to such problems should involve students thinking about and explaining relationships. This could include characteristics of a problem that allow it to be classified as a particular type in relation to strategies that could be used to solve each type of problem. It could also include recognizing the relationship between the type of knowledge and what level of representations of knowledge is required to communicate the chemistry concepts involved. The suggestions for teaching that follow are likely found elsewhere in the literature; however, they would differ here in their specificity to electrochemistry and the three categories that were used in the framework of analysis in this study.

The use of a decision routine is an efficient strategy for solving routine problems, especially when those problems are most commonly encountered. Electrochemical cell concepts; however, are very similar for both routine and non-routine voltaic cells and electrolytic cells. The use of non-routine cells, such as those with inert electrodes and electrolytic cells, in both demonstrations and laboratory activities would increase the range of contexts that students experience while learning the concepts. Students could identify the differences in the types of electrochemical cells but they did not transfer their procedural knowledge between voltaic cells and electrolytic cells. Similarly, for routine cells students could more easily relate the levels of representation of knowledge but they did not seem to be able to transfer this skill to less familiar electrochemical cells. Although problems had been demonstrated for each type of electrochemical cell during the lessons observed in this unit, the students did not seem to recognize how the underlying chemical processes were related. They focused on the differences, and so were unable to flexibly use the decision routines. In part, this may result because the majority of instructional and learning time was directed towards routine voltaic cells. If students were required to make their decision routines explicit, received instruction on how to recognize different problem contexts, and were helped to decompartmentalize their thinking about the macroscopic, particulate and symbolic levels of representation, then problem-solving might be developed in a more flexible manner. For example, students can use procedural knowledge to identify the strongest oxidizing agent on redox table. However, conceptual knowledge is required to explain what characteristics of a substance allow it to be a good oxidizing agent. Similarly, students can identify a spontaneous reaction by applying a recognizable pattern to the redox table. The selection of a material for a container in which to store a strong oxidizing agent requires meaningful learning of the underlying chemistry because the problem goes beyond the application of a definition or recognition of a pattern. By reducing the emphasis on the correct answer as a goal of problem solving, and increasing the value of the ability to communicate why a strategy is chosen and how it can be applied, students may begin to move towards a deeper understanding of chemistry concepts.

The presentation of all three levels of representation of knowledge in lessons would make the relationship between the levels more explicit for students. The visualization of chemical reactions at the microscopic level enables students to create mental representations of those reactions and the development of a linked visual-verbal mental structure should promote problem-solving and transfer. This could be accomplished in a number of ways.

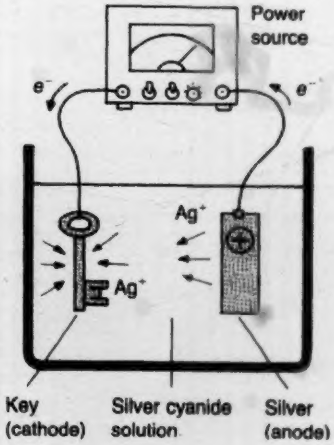
Students could be required to use all three levels of representation on diagrams of both routine and non-routine electrochemical cells. These diagrams were available for students (see Figure 5-3) but were found in fewer than 10% of the diagrams in the student textbook. More typically, diagrams contained one or two levels of representation (see Figure 5-4).

Figure 5-3. A voltaic cell diagram showing three levels of representation of knowledge in chemistry: symbolic, macroscopic, and particulate.


e^-
e^-
$Ag_{(s)}$
$Na^+_{(aq)}$
$NO_3^-{}_{(aq)}$
$Cu_{(s)}$
cathode (+)
anode (–)
$Ag^+_{(aq)}$
$Na^+_{(aq)}$
$NO_3^-{}_{(aq)}$
$Ag^+_{(aq)}$
$NO_3^-{}_{(aq)}$
$Cu^{2+}_{(aq)}$
$Cu^{2+}_{(aq)}$
$NO_3^-{}_{(aq)}$
$Cu^{2+}_{(aq)}$
$NO_3^-{}_{(aq)}$
cathode half-cell
$Ag^+_{(aq)} + e^- \rightarrow Ag_{(s)}$
(reduction)
anode half-cell
$Cu_{(s)} \rightarrow Cu^{2+}_{(aq)} + 2e^-$
(oxidation)

From: [1]*Nelson Chemistry* (1993), p. 397

Figure 5-4. A voltaic cell diagram showing the particulate level of representation of knowledge in chemistry


Power source
e^-
e^-
Ag^+
Ag^+
Key (cathode)
Silver cyanide solution
Silver (anode)

From: [2]*Addison-Wesley Chemistry*, (1993), p. 520

---

[1] Jenkins et al., *Nelson Chemistry*. © 1993. Nelson Education Ltd. Reproduced by permission. www.cengage.com/permissions.

[2] Wilbraham et al,, Addison-Wesley Chemistry, © 1993. Pearson Education Canada. Reproduced by permission.

To improve the ability of students to develop the conceptual knowledge needed to transfer among the levels of representation, lessons and activities could be designed to include each level. Explaining the relationship among the levels could be the goal of the lesson rather than completing the task at each level in isolation. Indeed, Chittleborough and Treagust (2008) concluded that poor transfer between the levels of representation limited students' laboratory learning when diagrams were a component of the instructions in the laboratory. This implies that teachers must remain vigilant when using different forms of symbolic representation, (e.g., tables, diagrams, equations, chemical formulas) to determine whether students are making appropriate connections to the concepts being studied. Some students in this study reported that the use of video demonstrations or particulate animations helped them to visual the abstract nature of electron and ion movement in voltaic cells. When this type of visualization is used in conjunction with symbolic and macroscopic presentations, students can develop conceptual knowledge because the concepts at each of the three levels can now be seen to be related. Techniques to promote visualization of the abstract concepts involving the particulate level of representation can be powerful explanatory tools; however, they may only effectively contribute to learning when used in a constructivist manner.

A laboratory activity observed in this study involved setting up and observing four different voltaic cells. At their desks, students first wrote the equations using their redox table and calculated the theoretical cell potential. Then they moved to the laboratory to set up the cells and recorded the observed voltage. This approach seemed to promote the development of procedural knowledge because it separated the use of the symbolic and macroscopic representations, and did not address the particulate level of representation. If students were asked to set up a voltaic cell and reach a consensus in their group to explain their observations using all three levels of representation, then students more likely could be able to develop decision routines based on more than procedural knowledge in the laboratory. It would also involve a multiple modality activity because students would be using visual, tactile, and auditory modes to process the information. To further enrich the activity, students could be encouraged to practice with different types of problems, such as exploring the effect of altering the cell design on the operation of the cell. Examples of this were used in the task-based interview in this study.

It is recommended that the teaching of electrochemistry begin with a more familiar, battery-like apparatus rather than beginning with a copper-zinc research cell. Johnstone (1982, 1991) maintained that one reason for the lack of conceptual knowledge resulting from laboratory instruction was that many concepts in chemistry are not directly observed and students do not link what they observe at the macroscopic level with what they are expected to learn at the particulate level. Chemistry educators need to reflect on taking the next step to examine teaching strategies that move students forward from their present ideas about scientific conceptions to those that are more accepted by the scientific community (Treagust, Duit, & Fraser, 1996). Problem tasks that are routine are done procedurally by students without understanding but by using an idea in a slightly different or novel context, misunderstandings could be identified and possibly confronted.

In teaching problem solving, show students the physical entities and ask them to describe the problem in terms of the physical phenomena involved on both the macroscopic and microscopic level. Make the transfer between levels of representation more frequently and more explicitly for students. Use multiple representations for students. When molecular animations and video demonstrations are used, students seemed to better correlate all three levels of representation, develop conceptual knowledge of the electrochemical cell, and hold fewer alternative conceptions because an accurate mental model has a greater potential to be developed. By improving the way teachers and students use chemical diagrams, animations, and other visualization tools, the connections between the various levels of representation of knowledge in chemistry could be improved.

Limitations of the Study

There are a number of limitations evident in this research. Although it is hoped that this research will have a broader application, it may not be generalizable to other contexts or populations because of its specificity to the field of high school electrochemistry in Alberta. The sample was limited to two urban high schools and the results may not be generalizable to other settings that may follow a different program of studies. The self-developed, main study diagnostic instrument did not undergo a large scale validation which may have identified inherent weaknesses in its design.

Suggestions for Further Study

Modifications in the diagnostic instrument could be carried out in order to study the alternative conceptions and types of knowledge used in other topics at the high school level, such as the particulate nature of matter. Refinements could also be made to the diagnostic instrument to identify further alternative conceptions in electrochemistry and the relationships that may exist among them. Additionally, problems could be developed to determine the ability of students to relate the three levels of representation of knowledge in chemistry. The approach used in this study also seemed amenable to identifying types of knowledge and alternative conceptions related to specific areas of science that may occur among elementary and junior high school science students.

Students developed a limited number of decision routines based on procedural knowledge that they did not seem to be able to transfer to different problem contexts. The effect of specific instruction in identifying problem types and problem contexts on the ability to solve problems, and the type of knowledge used to solve problems, could inform teaching practice.

The effect of explicit instruction on decision routines and the levels of representation of knowledge in chemistry on conceptual knowledge acquisition by students could be explored to determine their impact of problem-solving strategies developed and used by students.

Despite the growing literature on students' alternative conceptions, teachers in this study were not aware of those research results. Appropriate information, curriculum materials, and supplies should be developed to support implementation of the constructivist approach to learning in classrooms.

This study contributes to the body of knowledge that already exists by exemplifying that current science instruction often fails to promote the development of conceptual knowledge in electrochemistry, but that the problem is more complex than previously reported. Much work remains to be done in developing and refining teaching strategies that are both effective and fit the realities of schools, before these approaches are introduced into classrooms.

This study explored the alternative conceptions that students held in electrochemistry but did not look at the development of ideas over time. Thus in order to track changes in students conceptions which result from instruction, and identify factors which influence an individual to change their ideas, further study might include an in-depth study with a limited number of students or groups of students involving frequent interviews to track the development of their ideas during the unit of study.

In addition to the classroom situation, another key factor which influences success in conceptual change is the students themselves. Only the student can decide whether they will accept, reject, or revise ideas, and decide whether they will strive for deeper understanding. Their motivation is implicit in this notion of hot conceptual change.

Therefore, it might be useful to explore how conceptual change strategies affect students of different ability levels and why students choose to accept or reject the ideas developed in class. The findings would be beneficial for developing strategies which are appropriate for students with varying levels of talent or motivation.

Final Words

It is important to emphasize the need for a change of perspective. The intent of a reinvention approach is to help the students generate useful and meaningful knowledge on their own level and at their own pace. This goal implies that students are to develop an attitude in which the first objective is that of meaningful learning and coming to grips with the problem instead of looking at problems as instances of applications of some procedural toolkit. Within this orientation, the facts and procedures that dominate in procedural knowledge are not the point of departure; instead, students get the opportunity to develop their own conceptual knowledge.

The test questions developed in this study could be used by teachers to find out whether specific alternative conceptions appear in their classroom and may serve to open conversations about alternative theories. However, recognizing an alternative conception is not the same thing as accepting it as inadequate, and teachers must develop skill at fomenting conceptual conflict in their students while motivating them to come to place more value on the attainment of conceptual knowledge. From a constructive perspective, this can be done by challenging students with non-routine problems that require them to find relationships between their existing knowledge and new conceptions and helping them to explain their choices and decisions in a social setting. The assessment of learning could then begin to shift from a comparison between information presented by the teacher and that acquired by the student, to focus on the sense-making of the individual. This would allow students to develop a more usable toolkit to deal with the ever increasing growth of easily accessible information, and shift the meaning of "knowing" from being able to remember and repeat information to being able to find and use it effectively and efficiently.

REFERENCES

Abd-El-Khalick, F., Lederman, N.G., Bell, R.L., & Schwartz, R.S. (2001). View of nature of science questionnaire (VNOS): toward valid and meaningful assess[illegible] of learners' conceptions of nature of science. In *Proceedings of the annual meeting of the association for the education of teachers in science.* January 18-21. Costa Mesa, CA.

Abimbola, I.O., & Baba, S. (1996). Misconceptions and Alternative Conceptions in Science Textbooks: The Role of Teachers as Filters, *American Biology Teacher,* 58(1), 14-19.

Abraham, M.R., Grzybowski, E.B., Renner, J.W., & Marek, E.A. (1992). Understandings and misunderstandings of eighth graders of five chemistry concepts found in textbooks. *Journal of Research in Science Teaching,* 29, 106.

Acar, B., & Tarhan, L. (2007). Effect of cooperative learning strategies on students' understanding of concepts in electrochemistry. *International Journal of Science and Mathematics Education*, 5(2), 349-373.

Access: The Education Station (Producer). (1996). Chemistry Connections: Electrochemical Changes - Electrolysis [Video recording]. Available from Access: The Education Station, 3720 77B Ave, Edmonton, AB T6B 2N9.

Addison-Wesley Chemistry, SI Edition. (1993). Wilbraham, A.C., Staley, D.D., Simpson, C.J., & Matta, M.S. Don Mills, ON: Addison-Wesley Publishers.

Alberta Education. (1996). Science (Elementary). Government of Alberta, Alberta, Canada. Retrieved December 4, 2007, from http://www.education.gov.ab.ca/k_12/curriculum/bySubject/science/elemsci.pdf

Alberta Education. (2003). Science Grade 7-8-9. Government of Alberta, Alberta, Canada. Retrieved December 4, 2007, from http://www.education.gov.ab.ca/k_12/curriculum/bySubject/science/sci7to9.pdf

Alberta Education. (2005a). Science 10. Government of Alberta, Alberta, Canada. Retrieved December 4, 2007, from http://education.alberta.ca/media/654833/science10.pdf

Alberta Education. (2005b). Chemistry 30 Released Diploma Examination Items. Government of Alberta, Alberta, Canada

Alberta Education. (2006a). Chemistry 30 2005-2006 Assessment Highlights. Government of Alberta, Alberta, Canada. Retrieved July 31, 2007, from http://www.education.gov.ab.ca/k_12/curriculum/bySubject/science/scintro.pdf

Alberta Education. (2006b). Chemistry 30 Released Diploma Examination Items. Government of Alberta, Alberta, Canada

Alberta Education. (2007a). Chemistry 20-30 Program of Studies. Government of Alberta, Alberta, Canada. Retrieved December 4, 2007, from http://www.education.gov.ab.ca/k_12/curriculum/bySubject/science/chem2030_07.pdf

Alberta Education. (2007b). Chemistry 30 2006-2007 Assessment Highlights. Government of Alberta, Alberta, Canada. Retrieved December 4, 2007, from http://www.education.gov.ab.ca/k_12/testing/documents/dip/chem30_assessment_highlights.pdf

Alberta Education. (2008a). Chemistry Data Booklet. Government of Alberta, Alberta, Canada. Retrieved March 3, 2008, from http://www.education.gov.ab.ca/k_12/testing/diploma/chem30_databooklet.pdf

Alberta Education. (2008b). Diploma Math/Science Examinations and Key Archive. Government of Alberta, Alberta, Canada. Retrieved April 14, 2008, from http://education.alberta.ca/students/exams/answerkeys.aspx

Alberta Education. (2008c). Chemistry 30 2007-2008 Assessment Highlights. Government of Alberta, Alberta, Canada. Retrieved August 4, 2008, from http://www.education.gov.ab.ca/k_12/testing/documents/dip/chem30_assessment_highlights.pdf

Anderson, L. W., & Krathwohl, D. R. (Eds.), (2001). *A taxonomy for learning, teaching, and assessing: A revision of Bloom's taxonomy of educational objectives.* New York: Longman.

Arnaudin, M.W., & Mintzes, J.J. (1985). Students' alternative conceptions of the human circulatory system: A cross age study. *Science Education*, 69, 721-733.

Atherton, J.S. (2005). *Learning and teaching: Resistance to learning.* Retrieved August 7, 2008, from, http://www.dmu.ac.uk/~jamesa/learning/resistan.htm.

Ausubel, D. (1968). *Educational Psychology: A Cognitive View.* Boston, MA: Holt, Rinehart, & Winston.

Ausubel, D.P. (2000). *The acquisition and retention of knowledge: A cognitive view.* Dordrecht, The Netherlands: Kluwer Academic Publishers.

Barak, M., & Dori, Y.J. (2005). Enhancing undergraduate students' chemistry understanding through project-based learning in an IT environment. *Science Education*, 89(1), 117-139.

Barnett, S.M., & Koslowski, B. (2002). Adaptive expertise: effects of type of experience and the level of theoretical understanding it generates. *Thinking and Reasoning*, 8(4), 237-267.

Beck, C. & Kosnik, C. (2006). *Innovation in teacher education:. A social constructivist approach.* Albany, NY: State University of New York Press.

Bell, R.L., Smetana, L. & Binns, I. (2005). Simplifying inquiry instruction. *The Science Teacher*. October, 30-33. Washington, DC: National Science Teachers Association. Retrieved November 3, 2007, from http://www.nsta.org/main/news/stories/science_teacher.php?news_story_ID=50983

Berube, C.T. (2004). Are standards preventing good teaching? *The Clearing House,* 77(6), 264-267.

Bodner, G.M.J. (1986). Constructivism: A theory of knowledge. *Journal of Chemical Education,* 63, 873-878.

Bodner, G.M. (1987). The role of algorithms in teaching problem-solving. *Journal of Chemical Education,* 64, 513-514.

Bodner, G.M., & Herron, J.D. (2002). Problem-solving in chemistry. In Gilbert, J.K., de Jong, O., Justi, R., Treagust, D.F., & van Driel, J. *Chemical education: Towards research-based practice* (pp 235-266). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Bogdan, R.C., & Biklen, S.K. 1992. *Qualitative research for education: An introduction to theory and methods.* Boston. MA: Allyn and Bacon.

Bojczuk, M. (1982). Topic difficulties in O- and A-level chemistry. *School Science Review,* 64, 545-551.

BouJaoude, S., & Barakat, H. (2000). Secondary students' difficulties with stoichiometry. *School Science Review*, 81(286), 91-98.

Bowen, C., & Bunce, D.M. (1997). Testing for conceptual understanding in general chemistry. *The Chemical Educator,* 2(2), 1-17.

Bransford, J.D., Brown, A.L., & Cocking, R.R., (Eds.), (1999). *How people learn: Brain, mind, experience, and school.* Washington, DC: National Research Council, National Academy Press. Retrieved August 14, 2007, from http://site.ebrary.com/lib/albertaac/Doc?id=10041047&ppg=270

Bransford, J.D., & Stein, B.S. (1993). The IDEAL Problem Solver. New York, NY: Freeman. In J. D. Bransford (Ed.), *How People Learn: Brain, Mind, Experience, and School.* Washington, DC, USA: National Academies Press, (p. 241). Retrieved August 24, 2007, from http://site.ebrary.com/lib/albertaac/Doc?id=10041047&ppg=267

Briggs, D.C., Alonzo, A., Schwab, C., & Wilson, M. (2006). Diagnostic assessment with ordered multiple-choice items. *Educational Assessment,* 11(1), 33-63.

Bröder, A., & Schiffer, S. (2006). Adaptive Flexibility and Maladaptive Routines in Selecting Fast and Frugal Decision Strategies. *Journal of Experimental Psychology: Learning, Memory, and Cognition,* 32(4), 904–918.

Brownell, W. A. (1956). Meaning and skill–maintaining the balance. *The Arithmetic Teacher*, 3(4), 129-136.

Bruner, J. (1986). *Actual minds, possible worlds.* Cambridge, MA: Harvard University Press.

Bruyn, S. (1966). *The human perspective in sociology: The methodology of participant observation*. Englewood Cliffs, NJ: Prentice-Hall.

Bunce, D.M. (1993). Introduction: Symposium: Lecture and learning: Are they compatible? *Journal of Chemical Education,* 70, 179-180.

Burke, K.A., Greenbowe, T.J., & Windschitl, M.A. (1998). Developing and using conceptual computer animations for chemistry instruction. *Journal of Chemical Education,* 75, 1658-1661.

Butts, B., & Smith, R. (1987). What do students perceive as difficult in HSC chemistry? *Australian Science Teachers Journal,* 32, 45-51.

Bybee, R.W. (1997). *Achieving scientific literacy: From purposes to practice.* Portsmouth, NH: Heinemann.

Canadian Oxford Dictionary. (2004). Don Mills, ON: Oxford University Press.

Caramazza, A., McClosley, M., & Green, B. (1981). Naïve beliefs in "sophisticated" subjects: Misconceptions about trajectory of objects. *Cognition,* 9, 117-123.

Carey, S. (1986). Cognitive science and science education. *American Psychologist,* 41, 1123-1130.

Carson, R.N. (2004). A taxonomy of knowledge types for use in curriculum design. *Interchange*, 35(1), 59-79.

Cawthron. E.R., & Rowell, J.A. (1978). Epistemology and science education. *Studies in Science Education*, 5, 31-59.

Champagne, A., Gunstone, R., & Klopfer, L. (1985). Effecting change in cognitive structure among physics students. In L.H.T. West, & A.L. Pines (Eds.), *Cognitive structure and conceptual change* (pp. 163-187). New York, NY: Academic Press.

Chase, W.G., & Simon, H.A. (1973). Perception in chess. *Cognitive Psychology,* 1, 33-81.

Chi, M.T.H. (1997). Quantifying qualitative analyses of verbal data: A practical guide. *Journal of the Learning Sciences*, 6(3), 271–315.

Chi, M.T.H., Bassok, M., Lewis, M.W., Reimann, P., & Glaser, R. (1989). Self-explanations: How students study and use examples in learning to solve problems. *Cognitive Science,* 15, 145–182.

Chi, M.T.H., de Leeuw, N., Chui, M-H, & Lavancher, C. (1994). Eliciting self-explanations improves understanding. *Cognitive Science,* 18, 439-477.

Chi, M. T. H., Feltovich, P.J., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science,* 5, 121-152.

Chiapetta, E.L., Fillman, D.A., & Sethna, G.H. (1991). A method to quantify major themes of scientific literacy in science textbooks. *Journal of Research in Science Teaching*, 28(8), 713-725.

Chittleborough, G., & Treagust, D. (2008). Correct interpretation of chemical diagrams requires transforming from one level of representation to another. *Research in Science Education*, 38, 463-482.

Cho, H., Kahle, J.B., & Nordland, F.H. (1985). An investigation of high school textbooks as sources of misconceptions and difficulties in genetics and some suggestions for teaching genetics. *Science Education*, 69, 707-719.

Clerk, D., & Rutherford, M. (2000). Language as a confounding variable in the diagnosis of misconceptions. *International Journal of Science Education,* 22(7), 703-717.

Council of Ministers of Education, Canada (CMEC). (1996). *Science assessment: Framework and criteria, School achievement indicators program.* Toronto, ON: SAIP.

Creswell, J.W. (2002). *Educational research: Planning, conducting, and evaluating quantitative and qualitative research.* Upper Saddle Drive, New Jersey: Pearson Education.

Crick, M.D., Jones, M.G., & Jones, B.D. (2003). *The unintended consequences of high-stakes testing*. Oxford, UK: Rowan & Littlefield Publishers.

Dahsah, C., & Coll, R.C. (2007). Thai grade 10 and 11 students' conceptual understanding and ability to solve stoichiometry problems. *Research in Science and Technological Education,* 25(2), 227-241.

Dana, T.M., & Davis, N.T. (1993). On considering constructivism for improving mathematics and science teaching and learning. In *The Practice of Constructivism in Science Education* (pp. 235-334). Hillsdale, NJ: Laurence Erlbaum.

Darling-Hammond, L. (1991). The implications of testing policy for quality and equality. Phi Delta Kappan, 73(3), 220-225.

Davis, B. (2004). *Inventions of Teaching: A Genealogy*. Hillsdale, NJ: Lawrence Erlbaum.

De Jong, O., Acampo, J., & Verdonk, A. (1995). Problems in teaching the topic of redox reactions: Actions and conceptions of chemistry teachers. *Journal of Research in Science Teaching,* 32(10), 1097-1110.

De Jong, O., & Treagust, D.F. (2002). The teaching and learning of electrochemistry. In: J. Gilbert, O. de Jong, R. Justi, D. Treagust, & J. van Driel (Eds.), *Chemical Education: Towards Research-based Practice* (pp. 317-337). Dordrecht, The Netherlands: Kluwer Academic Publishers.

De Jong, O., & van Driel, J. (2001). The development of prospective teachers' concerns about teaching chemistry topics at a macro-micro-symbolic interface. In H. Behrendt (Ed.), *Research in Science Education – Past, Present, and Future* (pp. 271-276). The Netherlands: Kluwer Academic Publishers.

Denzin, N.K., & Lincoln, Y.S. (1994). Introduction: Entering the field of qualitative research. In N.K Denzin & Y.S. Lincoln (Eds.), *Handbook of qualitative research* (pp. 1-17). Thousand Oaks, CA: Sage.

Denzin,N.K.& Lincoln, Y.S. (2005). The discipline and practice of qualitative research. In N.K Denzin & Y.S. Lincoln (Eds.). *The Sage handbook of qualitative research* (3rd ed., pp. 1-32). Thousand Oaks, CA: Sage.

DiLisi, G.A., Eulberg, J.E., Lanese, J.F., & Padovan, P. (2006). Establishing problem-solving habits in introductory science courses. *Journal of College Science Teaching*, 35(5), 42-49.

Denzin, N.K. (1994). The art and politics of interpretation. In N.K. Denzin & Y.S. Lincoln (Eds.), *Handbook of Qualitative Research Design* (pp. 500-515). Thousand Oaks, CA: Sage.

DeWalt, K.M., & DeWalt, B.R. (2001). *Participant observation: A guide for fieldworkers.* Lanham, MD: Rowman & Littlefield Publishing.

Diesing, P. (1972). *Patterns of discovery in the social sciences.* London, England: Routledge & Kegan Paul.

Driver, R. (1981). Pupil's alternative frameworks in science. *European Journal of Science Education,* 3, 93-101.

Driver, R. (1986, April). *Restructuring the science curriculum: The approach of the children's learning in science project.* Paper presented at the annual meeting of the American Educational Research Association, San Francisco, CA.

Driver, R., & Easley, J. (1978). Pupils and paradigms: A review of literature related to concept development in adolescent science students. *Studies in Science Education,* 5, 61-84.

Driver, R., & Erickson, G. (1983). Theories-in-action: Some theoretical and empirical issues in the study of students' conceptual frameworks in science. *Studies in Science Education,* 10, 37-60.

Driver, R., Guesne, E., & Tiberghein, A. (1985). C*hildren's Ideas in Science.* Buckingham, England: Open University Press. In V. Talanquer (2006). Commonsense chemistry: a model for understanding students' alternative conceptions. *Journal of Chemical Education*, 83(5), 811-816.

Driver, R., & Oldham, V. (1986). A constructivist approach to curriculum development in science. *Studies in Science Education,* 13, 105-122.

Duit, R. (2007*). Bibliography: Students' and teachers' conceptions and science education.* Retrieved March 3, 2008, from http://www.ipn.uni-kiel.de/aktuell/stcse/stcse.html

Duit, R., & Treagust, D.F. (1998). Learning in science: From behaviorism towards social constructivism and beyond. In N.K. Fraser & K.G. Tobin (Eds.), *International Handbook of Science Education* (pp. 3-25). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Duschl, R.A., & Gittomer, D.H. (1991). Epistemological perspectives on conceptual change: Implications for educational practice. *Journal of Research in Science Teaching,* 28(9), 839-858.

Ellis, J. (1998). Interpretive inquiry as a formal research process. In J. Ellis (Ed.), *Teaching from Understanding. Teacher as interpretive inquirer* (pp. 15-32). New York, NY: Garland.

Ellis, J. (2006). Researching children's experience hermeneutically and holistically. *Alberta Journal of Educational Research,* 52(3), 111-126.

Fensham, P. (2000). Providing suitable content in the 'science for all' curriculum. In R. Miller, J. Leach, & J. Osbourne (Eds.), *Improving science education: The contribution of research.* Buckingham, England: Open University Press.

Finley, F.N., Stewart, J., & Yarroch, W.L. (1982). Teachers' perceptions of important and difficult science content. *Science Education*, 66, 531-538.

Fisher, K.M. (1985). A misconception in biology: amino acids and translation. *Journal of Research in Science Teaching,* 2, 53-62.

Fisher, K.M., & Lipson, J.I. (1986). Twenty questions about student errors. *Journal of Research in Science Teaching,* 23, 783-893.

Freire, P. (1970). *Pedagogy of the oppressed.* New York, NY: The Seabury Press.

Furió-Más, C., Calatayud, M-L., & Bárcenas, S.L. (2007). Surveying students' conceptual and procedural knowledge of acid-base behavior of substances. *Journal of Chemical Education*, 84(10), 1717-1724.

Gabel, D. (1986). *Problem solving in chemistry: Research matters... to the science teacher.* Washington: National Association for Research in Science Teaching.

Gabel, D. (1998). The complexity of chemistry and implications for teaching. In B.J. Fraser & K.G. Tobin (Eds.), *International Handbook of Science Education* (pp. 233-248). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Gabel, D.L., & Bunce, D.M. (1994). Research on problem solving: Chemistry. In D. Gabel (Ed.), *Handbook of Research on Science Teaching and Learning* (pp. 301-326). London: Kluwer Academic Publishers.

Gabel, D.L., Sherwood, R.D., & Enochs, L. (1984). Problem solving skills of high school chemistry students. *Journal of Research in Science Teaching,* 21, 221-233.

Gangoso, Z., Moyano, T., Buteler, L., Coleoni, E., & Gattoni, A. (2006). Teaching strategies for physics problem solving: Relations to student performance. *Journal of Science Education*, 7(2), 98-102.

Garnett, P.J., & Treagust, D.F. (1992a). Conceptual difficulties experienced by senior high school students of electrochemistry: Electric circuits and oxidation-reduction equations. *Journal of Research in Science Teaching,* 29(2), 121-142.

Garnett, P.J., & Treagust, D.F. (1992b). Conceptual difficulties experienced by senior high school students of electrochemistry: Electrochemical (galvanic) and electrolytic cells. *Journal of Research in Science Teaching,* 29(10), 1079-1099.

Geelan, D.R. (1997). Epistemological anarchy and the many forms of constructivism. *Science and Education,* 6, 15-28.

Gilbert, J.K., Osborne, R.J., & Fensham, P.J. (1982). Children's science and its consequences for teaching. *Science Education,* 66, 623-633.

Gil-Perez, D., & Carrascosa, J. (1990). What to do about science misconceptions. *Science Education,* 74(5), 531-540.

Glaser, R. (1984). Education and thinking: The role of knowledge. *American Psychologist,* 39, 93-104.

Gobet, F. (2005). Chunking models of expertise: Implications for education. *Applied Cognitive Psychology,* 19, 183-204.

Goldin, G.A. (2000). A scientific perspective on structured, task-based interviews in mathematics education research. In A.E. Kelly & R.A. Lesh (Eds.), *Handbook of research design in mathematics and science education* (pp. 517-545). Mahwah, NJ: Lawrence Erlbaum.

Goodwin, A. (2000). The teaching of chemistry: who is the learner? *Chemical Education: Research and Practice in Europe,* 1, 51-60.

Gott, R., Duggan, S., & Johnson, P. (1999). What do practising and applied scientists do and what are the implications for science education? *Research in Science & Technological Education,* 17(1), 97-107.

Greene, J.C. (2007). *Mixed Methods in Social Inquiry.* San Francisco, CA: Jossey-Bass.

Greene, J., Caracelli, V., & Graham, W. (1989). Toward a conceptual framework for mixed method evaluation designs. *Educational Evaluation and Policy Analysis,* 11(3), 225-274.

Greenbowe, T.J. (1994). An interactive multimedia software program for exploring electrochemical cells. *Journal of Chemical Education,* 71, 555-557.

Grey, P., & Costello, M. (1987). *Context as a determinant of methodology in multi-client service organizations.* Paper presented at the annual meeting of the American Evaluation Association, Boston, MA.

Griffiths, A.K. (1994). A critical analysis and synthesis of research on students' chemistry misconceptions. In H.J. Schmidt (Ed.), *Problem solving and misconceptions in chemistry and physics* (pp. 70-99). Hong Kong: ICASE.

Griffiths, A.K., & Grant, B.A.C. (1985). High school students' understanding of food webs: Identification of a learning hierarchy and related misconceptions. *Journal of Research in Science Teaching, 22*, 421-436.

Guba, E.G., & Lincoln, Y.S. (1989). *Fourth generation evaluation.* Newbury Park, CA: Sage.

Guba, E.G., & Lincoln, Y.S. (1994). Competing paradigms in qualitative research. In N.K. Denzin & Y.S. Lincoln (Eds.). *Handbook of qualitative research* (pp. 105-117). Thousand Oaks, CA: Sage.

Guba, E.G. & Lincoln, Y.S. (2005). Paradigmatic controversies, contradictions, and emerging confluences. In N.K. Denzin & Y.S. Lincoln (Eds.). *The Sage handbook of qualitative research.* (3rd ed., pp. 191-213). Thousand Oaks, CA: Sage.

Han, J.Y. & Roth, W-M. (2006). Chemical inscriptions in korean textbooks: Semiotics of macro- and microworld. *Science Education*, 90(2), 173-201.

Haverty, L.A., Koedinger, K.R., Klahr, D., & Alibali, M.W. (2000). Solving inductive reasoning problems in mathematics: Not-so-trivial pursuit. *Cognitive Science,* 24(2), 249-298.

Hegel, G.W.F. (1995). *Lectures on the history of philosophy. I. Greek Philosophy to Plato.* (Translated: E.S. Haldane 1892, Originally published 1833) (p. 487). Lincoln, Nebraska: University of Nebraska Press.

Helm, H. (1980). Misconceptions in physics amongst South African students. *Physics Education,* 15, 92-105.

Herron, J.D. (1990). Research in chemical education: Results and directions. In M. Gardner, J.G. Green, F. Reif, A.H. Schoenfeld, A. Disessa, & E. Stage (Eds.), *Toward a scientific practice in science education* (pp. 31-54). Hillsdale, NJ: Erlbaum.

Herron, J.D., & Nurrenbern, S.C. (1999). Chemical education research: improving chemistry learning. *Journal of Chemical Education*, 76(10), 1353-1361.

Hestenes, D., Wells, M., & Swackhamer, G. (1992). Force concept inventory. *The Physics Teacher,* 30, 141-158.

Heyworth, R.M. (1999). Procedural and conceptual knowledge of expert and novice students for the solving of a basic problem in chemistry. *International Journal of Science Education,* 21(2), 195-211

Hiebert, J., & Lefevre, P. (1986). Conceptual and procedural knowledge in mathematics: an introductory analysis. In J. Hiebert (Ed.), *Conceptual and procedural knowledge: The case of mathematics* (pp. 1-27). Hillsdale, NJ: Lawrence Erlbaum.

Hodson, D. (1988). Toward a philosophically more valid science curriculum. *Science Education*, 72, 19-40.

Hodson, D. (2001). Inclusion without assimilation: science education from an anthropological and metacognitive perspective. *Canadian Journal of Science, Mathematics and Technology Education*, 1, 161-182.

Holt, J. (1964). *How Children Fail*. New York, NY: Pitman Publishing Corporation.

Huddle, P.A., White, M.D., & Rogers, F. (2000). Using a teaching model to correct known misconceptions in electrochemistry. *Journal of Chemical Education*, 77(1), 104-110.

Johnstone, A.H. (1982). Macro- and micro-chemistry. *School Science Review*, 64, 377-379.

Johnstone, A.H. (1991). Why is science difficult to learn? Things are seldom what they seem. *Journal of Computer Assisted Learning*, 7, 75-83.

Johnson, R.B. & Onwuegbuzie, A.J. (2004). Mixed methods research: A research paradigm whose time has come. *Educational Researcher*, 33(7), 14-26.

Keeves, J.P. (1998). Methods and processes in research in science education. In B.J. Fraser & K.G. Tobin (Eds.), *International handbook of science education* (pp. 1127-1153). London: Kluwer Academic Publishers.

Kelly, G.A. (1955). *The psychology of personal constructs*. (Vols. 1-2). New York, NY: W.W. Norton.

Koedinger, K.R., & Nathan, M.J. (2004). The real story behind story problems: Effects of representations on quantitative reasoning. *The Journal of the Learning Sciences*, 13(2), 129-164.

Koslowski, B. (1996). *Theory and Evidence*. Cambridge, MA: MIT Press.

Koslowski, B., Susman, A., & Serling, J. (1991). Conceptual vs technical understanding of evidence in scientific reasoning. In S.M. Barnett & B. Koslowski (2002). Adaptive expertise: Effects of type of experience and the level of theoretical understanding it generates. *Thinking and Reasoning*, 8(4), 237-267.

Krathwohl, D. (1998). *Methods of educational and social science research: An integrated approach* (2nd ed.). New York, NY: Addison-Wesley Educational Publishers.

Kruse, R.A., & Roehrig, G.H. (2005). A comparison study: Assessing teachers' conceptions with the chemistry concepts inventory. *Journal of Chemical Education*, 82(8), 1246-1250.

Kwen, B. (1996). Consistency and inconsistency in A level students' understandings of a number of chemical reactions. *Research in Science and Technology Education,* 14(1), 55-66.

Kuhn, T.S. (1970). *The structure of scientific revolutions.* Chicago, IL: The University of Chicago Press.

Larkin, J.H. (1983). The role of problem representation in physics. In A.L. Stevens & D. Gentner (Eds.), *Mental models* (pp. 75-99). Hillsdale, NY: Erlbaum.

Larochelle, M., Bednarz, N., & Garrison, J. (Eds.). (1998). *Constructivism and education* (pp. 305). Cambridge, UK: Cambridge University Press.

Lave, J. (1988). *Cognition in practice: Mind, mathematics and culture in everyday life.* Cambridge, UK: Cambridge University Press.

Lederman, N.G. (1992). Students' and teachers' conceptions of the nature of science: A view of the research. *Journal of Research in Science Teaching,* 29(4), 331-359.

Leedy, P. (1993). *Practical research: Planning and design.* (5th ed.). New York, NY: Macmillan Publishing Company.

Leman, T., & Burçin, A. (2007). Problem-based learning in an eleventh grade chemistry class: 'factors affecting cell potential". *Research in Science & Technological Education*, 25(3), 351-369.

Lewis, J., & Richie, J. (2003). Generalizing from qualitative research. In J. Ritchie & J. Lewis (Eds.), *Qualitative Research Practice. A guide for social science students and researchers* (pp. 263-286). Thousand Oaks, CA: Sage Publications.

Li, X., & Li, Y. (2008). Research on students' misconceptions to improve teaching and learning in school mathematics and science. *School Science and Mathematics*, 108(1), 4-7.

Lin, H-S., Yang, T.C., Chiu, H-L., & Chou, C-Y. (2002). Students' difficulties in learning electrochemistry. *Proceedings of the National Science Council,* 12(3), 100-105.

Low, R., & Sweller, J. (2005). The modality principle in multimedia learning. In R.E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 147-158). Cambridge, UK: Cambridge University Press.

Lyle, K.S., & Robinson, W.R. (2001). Teaching science problem solving: An overview of experimental work. *Journal of Chemical Education*, 78(9), 1162-1163.

Martin, B., & Brouwer, W. (1991). The sharing of personal science and the narrative elements in science education. *Science Education*, 75(6), 707-722.

Mason, L., Gava, M., & Boldrin, A. (2008). On warm conceptual change: The interplay of text, epistemological beliefs, and topic interest. *Journal of Educational Psychology*, 100(2), 291-309.

Mason, D.S., Shell. D.F., & Crawley, F.E. (1997). Differences in problem solving by nonscience majors in introductory chemistry on paired algorithmic-conceptual problems. *Journal of Research in Science Teaching,* 34(9), 905-923.

Matthews, M.R. (2002). Thomas Kuhn's impact on science education: What lessons can be learned? *Science Education*, 88, 90-118.

Mayer, R.E. (2003). Mathematical problem solving. In J.M. Royer (Ed.), *Mathematical Cognition* (pp. 69-92). Greenwich, CT: Information Age.

Mayer, R.E. (2005). Conceptual understanding versus computational skill. In Royer, J.M. *The Cognitive Revolution in Educational Psychology* (pp. 105-118). Greenwich, CT: Information Age.

Mayer, R.E. (2008). *Learning and Instruction.* (2nd ed.). Upper Saddle River, NJ: Pearson Education.

McCloskey, M. (1983). Intuitive physics. *Scientific American,* 248(4), 114-122.

McMahon, M. (1997). *Social constructivism and the world wide web - A paradigm for learning.* Paper presented at the ASCILITE conference. Perth, Australia. Retrieved August 7, 2008, from, http://www.ascilite.org.au/conferences/perth97/papers/Mcmahon/Mcmahon.html

Meaghan, D.E., & Casas, F.R. (1995). On the testing of standards and standardized achievement testing: Panacea, placebo, or pandora's Box? *Interchange*, 26(1), 33-58.

Meltzer, L. (Ed.). (2007). *Executive function in education: From theory to practice* (pp. 320). New York, NY: Guilford Publications.

Mintzes, J.J., & Wandersee, J.H. (1998). Research in science teaching and learning: A human constructivist view. In J.J. Mintzes, J.H. Wandersee, & J.D. Novak (Eds.), *Teaching science for understanding: A human constructivist view* (pp. 59-92). San Diego, CA: Academic Press.

Mintzes, J.J., Wandersee, J.H., & Novak, J.D. (Eds.), (2000). Assessing *science understanding: A human constructivist view.* San Diego, CA: Academic Press.

Mischel, T. (1971). Piaget: Cognitive conflict and the motivation of thought. In T. Mischel (Ed.), *Cognitive Development and Epistemology* (pp. 311-355). New York, NY: Academic Press.

Morrison, J.A., & Lederman, N.G. (2003). Science teachers' diagnosis and understanding of students' preconceptions. *Science Education*, 87, 849-867.

Mulford, D.R., & Robinson, W.R. (2002). An inventory for alternative conceptions among first-semester general chemistry students. *Journal of Chemical Education*, 79(6), 739-744.

Nakhleh, M.B. (1992). Why some students don't learn chemistry. *Journal of Chemical Education*, 69(3), 191-196.

Nakhleh, M.B. (1993). Are our students conceptual thinkers or algorithmic problem solvers? *Journal of Chemical Education*, 70, 52-55.

National Research Council. (1996). *National science education standards.* Washington, DC: National Academic Press.

Nelson Chemistry. (1993). Jenkins, F., van Kessel, H., & Tompkins, D. Scarborough, ON: Nelson Canada.

Newell, A., & Simon, H.A. (1972). *Human problem solving.* Englewood Cliffs, NJ: Prentice-Hall.

Niaz, M., & Chacon, E. (2003). A conceptual change teaching strategy to facilitate high school students' understanding in electrochemistry. *Journal of Science Education and Technology,* 12(2), 129-134.

Niaz, M., & Robinson, W.R. (1992). From 'algorithmic mode' to 'conceptual gestalt' in understanding the behaviour of gases: an epistemological perspective. *Research in Science and Technological Education,* 10, 53-64.

Nicoll, G. (2003). A qualitative investigation of undergraduate chemistry students' macroscopic interpretations of the submicroscopic structure of molecules. *Journal of Chemical Education*, 80(2), 205-213.

Nieswandt, M. (2007). Student affect and conceptual understanding in learning chemistry. *Journal of Research in Science Teaching*, 44(7), 908-937.

Novak, J.D. (1977). *A theory of education.* Ithaca, NY: Cornell University Press.

Novak, J. D., & Cañas, A. J. (2008). The Theory Underlying Concept Maps and How to Construct and Use Them, Technical Report IHMC CmapTools 2006-01 Rev 01-2008, Florida: Institute for Human and Machine Cognition. Retrieved September 20, 2008, from http://cmap.ihmc.us/Publications/ResearchPapers/TheoryUnderlyingConceptMaps.pdf

Nurrenbern, S., & Pickering, M. (1987). Concept learning versus problem solving: Is there a difference. *Journal of Chemical Education,* 64, 508-510.

Ogude, A.N., & Bradley, J.D. (1994). Ionic conduction and electrical neutrality in operating electrochemical cells. *Journal of Chemical Education*, 71(1), 29-34.

Ogude, A.N., & Bradley, J.D. (1996). Electrode processes and aspects relating to cell EMF, current, and cell components in operating electrochemical cells. *Journal of Chemical Education*, 73(12), 1145-1149.

Olakanmi, A.I., & Sakuhu, B. (1996). Misconceptions and alternative conceptions in science textbooks: The role of teachers as filters. *American Biology Teachers*, 58(1), 14-19.

Olson, J. (2008). More than a human endeavour. Science and Children, 45(6), 43-47.

O'Loughlin, M. (1992). Rethinking science education: beyond Piagetian constructivism towards a sociocultural model of teaching and learning. *Journal of Research in Science Teaching,* 29(8), 791-820.

Osborne, R.J., & Freyberg, R. (1985). *Learning in science: The implications for children's science.* Auckland, New Zealand: Heinemann.

Osborne, R., & Wittrock, M.C. (1983). Learning science: A generative process. *Science Education*, 67, 489-508.

Osborne, R.J., & Wittrock, M. (1985). The generative learning model and its implications for science education. *Studies in Science Education,* 12, 59-87.

Owen, E., & Sweller, J. (1985). What do students learn while solving mathematical problems? *Journal of Educational Psychology,* 77, 272-284.

Oxford Dictionary of Chemistry. (1996). (3rd ed.). Oxford, UK: Oxford University Press.

Ozkaya, A.R. (2002). Conceptual difficulties experience by prospective teachers in electrochemistry: half-cell potential, cell potential, and chemical and electrochemical equilibrium in galvanic cells. *Journal of Chemical Education*, 79(6), 735-738.

Pedrosa, M.A., & Dias, M.H. (2000). Chemistry textbook approaches to chemical equilibrium and student alternative conceptions. *Chemistry Education: Research and Practice in Europe,* 1(2), 227-236.

Pellegrino, J.W., Chudowsky, N., & Glaser, R. (2001). *Knowing what students know: The science and design of educational assessment.* Washington, DC: National Academy Press.

Perkins, D. (1993). Creating a culture of thinking. *Educational Leadership*, 51.

Perkins, D.N., & Unger, C. (1999). Teaching and learning for understanding. In C.M. Reigeluth (Ed.), *Instructional design theories and models* (pp. 91-114). Mahwah, NJ: LEA.

Peshkin, A. (1993). The goodness of qualitative research. *Educational Researcher,* 22(2), 24-30.

Peterson, R.F., & Treagust, D.F. (1989). Grade 12 students' misconceptions of covalent bonding and structure. *Journal of Chemical Education,* 66(6), 459-460.

Piaget, J. (1964). Cognitive development in children: Piaget, development and learning. *Journal of Research in Science Teaching,* 2, 176-180.

Piaget, J. (1972). *The child and reality: problems of genetic psychology.* Paris: Editions Denoel.

Pickering, M. (1990). Further studies on concept learning versus problem solving. *Journal of Chemical Education,* 67, 254-255.

Pines, A.L., & West, L.H.T. (1988). Conceptual understanding and science learning: An interpretation of research within a sources-of-knowledge framework. *Science Education,* 70, 583-604.

Pintrich, P.R., Marx, R.W., & Boyle, R.B. (1993). Beyond cold conceptual change: The role of motivational beliefs and classroom contextual factors in the process of conceptual change. *Review of Educational Research,* 63, 167-199.

Pollack, E., Chandler, P., & Sweller, J. (2002). Assimilating complex information. *Learning and Instruction,* 12, 61-86.

Popham, W. J. (2000). The mismeasurement of educational quality. *School Administrator*, 57(11), 12-15.

Pope, M., & Gilbert, J. (1985). Theories of learning: Kelly. In R. Osborne & J. Gilbert (Eds.), *Some issues of theory in science education* (pp. 19-41). Hamilton, New Zealand: University of Waikato.

Posner, G.J., Strike, K.A., Hewson, P.W., & Gertzog, W.A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education*, 66, 211-227.

Pushkin, D.B. (1998). Introductory students, conceptual understanding, and algorithmic success. *Journal of Chemical Education,* 75(7), 809-810.

Pushkin, D. (2007). Critical thinking and problem solving – the theory behind flexible thinking and skills development. *Journal of Science Education,* 8(1), 13-17.

Reid, N., & Yang, M-J. (2002). The solving of problems in chemistry: The more open-ended problems. *Research in Science & Technological Education*, 20(1), 83-98.

Renkl A., & Atkinson, R.K. (2002). Learning from examples: Fostering self-explanations in computer-based learning environments. *Interactive Learning Environment,* 10(2), 105-119.

Resnick, L. (Ed.), (1989). *Knowing, learning and instruction: Essays in honor of Robert Glaser.* Hillsdale, NJ: Lawrence Erlbaum.

Resnick, L.B., & Resnick, D.P. (1992). Assessing the thinking curriculum: New tools for educational reform. In B.R. Gifford & M.C. O'Connor (Eds.), *Changing assessments: Alternative views of aptitude, achievement and instruction* (pp. 37-75). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Roth, W.M. (1995). *Authentic school science: Knowing and learning in open-inquiry science laboratories.* Norwell, MA: Kluwer Academic Publishers.

Rumelhart, D.E., Smolensky, P., McClelland, J.L., & Hinton, G.E. (1986). Schematat and sequential thought processes in PDP models. In D.E. McClelland, D.E. Rumelhart, & The PDP research group (Eds.), *Parallel distributed processing: Explorations in the microstructure of cognition:. Vol. 1. Psychological and biological models (pp.* 7-57). Cambridge, MA: MIT Press.

Sadler, P. (2000). The relevance of multiple-choice testing in assessing science understanding. In J.J. Mintzes, J.H. Wandersee, & Novak, J.D. (Eds.), *Assessing science understanding: A human constructivist view.* San Diego: CA: Academic Press

Sanger, M.J., Brincks, E.L., Phelps, A.J., Pak, M.S., & Lyovkin, A.N. (2001). A comparison of secondary chemistry courses and chemistry teacher preparation programs in Iowa and Saint Petersburg, Russia. *Journal of Chemical Education*, 78(9), 1275-1280.

Sanger, M.J., Campbell, E., Felker, J., & Spencer, C. (2007). "Concept learning versus problem solving": Does particle motion have an effect? *Journal of Chemical Education*, 84(5), 875-880.

Sanger. M.J., & Greenbowe, T.J. (1997a). Students' misconceptions in electrochemistry: current flow in electrolyte solutions and the salt bridge. *Journal of Chemical Education*, 74(7), 819-823.

Sanger. M.J., & Greenbowe, T.J. (1997b). Common student misconceptions in electrochemistry: Galvanic, electrolytic, and concentration cells. *Journal of Research in Science Teaching*, 34(4), 377-398.

Sanger. M.J., & Greenbowe, T.J. (1999). An analysis of college chemistry textbooks as sources of misconceptions and errors in electrochemistry. *Journal of Chemical Education*, 76(6), 853-860.

Sanger, M.J., & Greenbowe, T.J. (2000). Addressing student misconceptions concerning electron flow in electrolyte solutions with instruction including computer animations and conceptual change strategies. *International Journal of Science Education*, 22(5), 521-537.

Sawrey, B. (1990). Concept learning versus problem solving: Revisited. *Journal of Chemical Education*, 67, 253-254.

Schowalter, V.M. (1974). What is united science education? (Part 5): Program objectives and scientific literacy. *Prism,* II(2), 3-4.

Science Council of Canada. (1984). *Science for every student.* Report 36. Ottawa, ON: Ministry of Supply and Service.

Science Focus 9. (2002). F. Allison (Ed.), Toronto, ON: McGraw-Hill Ryerson.

Scott, P., Asoko, H., & Driver, R. (1992). Teaching for conceptual change: A review of strategies. In R. Duit, F. Goldberg, & H. Neidderer (Eds.), *Research in physics learning: Theoretical issues of empirical studies* (pp. 310-329). Kiel, Germany: The University of Kiel.

Scott, P.H., & Driver, R.H. (1998). Learning about science teaching: Perspectives from an action research project. In B.J. Fraser, & K.G. Tobin (Eds.) *International Handbook of Science Education* (pp. 67-80). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Seidman, I.E. 1991. Technique isn't everything, but it is a lot. In *Interviewing as qualitative research: A guide for researchers in education and the social sciences* (pp. 56-71). New York, NY: Teachers College Press.

Selvaratnam, M., & Canagaratna, S.G. (2008). Using problem-solution maps to improve students' problem-solving skills. *Journal of Chemical Education*, 85(3), 381-385.

Sexena, A.B. (1991). The understanding of properties of light by students in India. *International Journal of Science Education,* 13(3), 283-289.

Shapiro, B.L. (1994). *What children bring to light: A constructivist perspective on children's learning in science.* New York, NY: Teacher's College Press.

Shuell, T.J. (1990). Phases of meaningful learning. *Review of Educational Research,* 60, 531-547.

Siegler, R.S. (1995). How does change occur: A microgenetic study of number conservation. *Cognitive Psychology,* 28, 225-273.

Simon, H. A. (1996). *Observations on the Sciences of Science Learning.* Paper prepared for the Committee on Developments in the Science of Learning for the Sciences of Science Learning: An Interdisciplinary Discussion. Department of Psychology, Carnegie Mellon University.

Sinatra, G.M. (2005). The "warming trend" in conceptual change research: The legacy of Paul R. Pintrich. *Educational Psychologist,* 40, 107-115.

Skemp, R.R. (1978). Relational understanding and instrumental understanding. *Arithmetic Teacher,* 26(3), 9-15.

Slotta, J.D., Chi, M.T.H., & Joram, E. (1995). Assessing students' misclassifications of physics concepts: An ontological basis for conceptual change. *Cognition and Instruction,* 13, 373-400.

Smith, F. (2002). *The glass wall. Why mathematics can seem difficult.* New York, NY: Teachers College Press.

Smith, S.R., & Abell, S.K. (2008). Assessing and addressing student science ideas. *Science and Children*, 45(7), 72-74.

Stewart, J. (1985). Cognitive science and science education. *European Journal of Science Education,* 7, 1-18.

Siegler, R.S. (2002). Microgenetic studies of self-explanation. In N. Garnott & J. Parziale (Eds.), *Microdevleopment: A process-oriented perspective for studying development and learning* (pp. 31-38). Cambridge, MA: Cambridge University Press.

Sloyer, C.W. (2003). Mathematical insight: Changing perspective. *The Mathematics Teacher,* 96(4), 238-243.

Sweller, J. (1988). Cognitive load during problem solving. *Cognitive Science,* 12, 257-285.

Sweller, J. (2006). How the human cognitive system deals with complexity. In J. Elan & R.E. Clark (Eds.), *Handling complexity in learning environments: Theory and research* (pp. 13-25). Amsterdam, The Netherlands: Elsevier

Taber, K.S. (2000). Challenging chemical alternative conceptions in the classroom? British Educational Research Association Annual Conference, Cardiff University, September 7-10, 2000.

Taber, K.S. (2001). Constructing chemical concepts in the classroom: Using research to inform practice. *Chemistry Education: Research and Practice in Europe,* 2, 43-51.

Talanquer, V. (2002). Minimizing misconceptions. *The Science Teacher,* 69(8), 46-49.

Talanquer, V. (2006). Commonsense chemistry: a model for understanding students' alternative conceptions. *Journal of Chemical Education*, 83(5), 811-816.

Thomas, P.L. (1997). *Student conceptions of equilibrium and fundamental thermodynamic concepts in college physical chemistry.* Unpublished PhD Thesis. University of Northern Colorado, Greeley, Colorado.

Thomas, R.M. (2005). High stakes testing: Coping with collateral damage. Mahwah, NJ: Lawrence Erlbaum Associates.

Tóth, Z., & Kiss, E. (2005). Hungarian secondary school students' strategies in solving stoichiometric problems. *Journal of Science Education*, 6(1), 47-49.

Treagust, D.F. (1988). Developing and use of diagnostic tests to evaluate students' misconceptions in science. *International Journal of Science Education,* 10, 159-169.

Treagust, D.F., Chittleborough, G., & Mamiala, T.L. (2002). Students' understanding of the role of scientific models in learning science. *International Journal of Science Education,* 24(4), 357-368.

Treagust, D.F., Duit, R., & Fraser, B. (Eds.), (1996). *Improving teaching and learning in science and mathematics.* New York, NY: Teachers College Press.

TV Ontario (Producer). (1986). Senior Chemistry: Electrochemical Cells [Video recording]. Available from TV Ontario: The Ontario Educational Communication Authority, Box 200, Station Q, Toronto, ON M4T 2T1

Valanides, N. (2000a). Primary student teachers' understanding of the process and effects of the particulate nature of matter and its transformations during dissolving. *Chemistry Education: Research and Practice in Europe,* 1, 249-262.

Valanides, N. (2000b). Primary student teachers' understanding of the process and effects of the process and effects of distillation. *Chemistry Education: Research and Practice in Europe,* 1, 355-264.

Valanides, N., Nicolaidou, A., & Eilks, I. (2003). Twelfth grade student' understanding of oxidation and combustion: Using action research to improve teachers' practical knowledge and teaching practice. *Research in Science and Technological Education,* 21(2), 159-175

Valera, F.J., Thompson, E., & Rosch, E. (1991). *The Embodied Mind.* Cambridge, MA: The MIT Press.

Velazquez-Marcano, A., Williamson, V.M., Ashkenazi, G., Tasker, R., & Williamson, K.C. (2004). The use of video demonstrations and particulate animation in general chemistry. *Journal of Science Education and Technology*, 13(3), 315-323.

Vosniadou, S. (2007), Conceptual change and education. *Human Development*, 50, 47–54.

Vygotsky, L.S. (1978). Mind in Society: The Development of the Higher Psychological Processes. Cambridge, MA: The Harvard University Press. (Original work published 1930, New York, NY: Oxford University Press.).

Wandersee, J.H., Mintzes, J.J., & Enusin, M.W. (1989). Biology from the learner's viewpoint: A content analysis of the research literature. *School Science and Mathematics,* 89, 654-668.

Wandersee, J.H., Mintzes, J.J., & Novak, J.D. (1994). Research on alternative conceptions in science. In D.L. Gabel (Ed.), *Handbook of research in science teaching and learning* (pp. 177-210). New York: Macmillan.

West, L.H., Fensham, P.J., & Garrard, J.E. (1985). In L.H. West, & A.L. Pines (Eds.), *Cognitive Structure and Conceptual Change.* Orlando, FL: Academic Press.

White, R., & Gunstone, R. (1992). *Probing understanding*. New York, NY: Falmer Press.

Wideen, M.F., O'Shea, M., Pye, I., & Ivany, G. (1997). High-stakes testing and the teaching of science. *Canadian Journal of Education*, 22(4), 428-444.

Williams, D.C., Ma, Y. Prejean, L., Ford, M.J., & Lai, G. (2008). Acquisition of physics content knowledge and scientific inquiry skills in a robotics summer camp. *Journal of Research on Technology in Education*, 40(2), 201-217.

Williamson, V., Huffman, J., & Peck, L. (2004). Testing students' use of the particulate theory. *Journal of Chemical Education*, 81(6), 891-896.

Wittrock, M.C. (1974). Learning as a generative process. *Educational Psychology*, 11, 86-95.

Wu, H-K. (2003). Linking the microscopic view of chemistry to real-life experiences: Intertextuality in a high-school science classroom. *Science Education*, 87(6), 868-891.

Wu, Y-T., & Tsai, C-C. (2005). Development of elementary school students' cognitive structures and information processing strategies under long-term constructivist-oriented science instruction. *Science Education,* 89(5), 822-846.

Yang, E-M., Andre, T., & Greenbowe, T.J. (2003). Spatial ability and the impact of visualization/animation on learning electrochemistry. *International Journal of Science Education,* 25(3), 329-349.

Yezierski, E.J., & Birk, J.P. (2006). Misconceptions about the particulate nature of matter: Using animations to close the gender gap. *Journal of Chemical Education*, 83(6), 954-960.

Young, M. (2003) Curriculum Studies and the Problem of Knowledge: updating the Enlightenment? *Policy Futures in Education*, 1(3), 553-564. Retrieved September 20, 2008, from http://dx.doi.org/10.2304/pfie.2003.1.3.7.

Appendix A: Electrochemistry Concepts
Modified from Garnett and Treagust (1992b), to be specific for the Alberta Education *Chemistry 30 Program of Studies* (1996).

Voltaic Cells

1. In a voltaic cell:
    a) there is a spontaneous chemical reaction which converts stored chemical energy into electrical energy
    b) the oxidation-reduction reaction which takes place is controlled and the oxidation and reduction half-reactions usually occur in separate compartments called half-cells
    c) a cell potential is spontaneously produced and an electric current results
    d) the relative tendencies of the reactants to be oxidized or reduced determines the resulting oxidation-reduction reaction
    e) the cell potential generated depends on the nature of the half-cell reactions
    f) the cell potential generated indicates the capacity of the cell to do electrical work
    g) the cell potential of the cell is measured in volts

2. Half cells
    a) are compartments in which separate oxidation and reduction half-reactions occur
    b) consist of an electrode immersed in an electrolyte
    c) are linked by a salt bridge which allows the transfer of ions in the internal circuit
    d) enable the transfer of electrons from one reactant to another to take place through an external circuit or metallic conductor which links the electrodes

3. Electrodes
    a) Electrodes are electrical conductors that are placed in an electrolyte to provide a surface for oxidation or reduction half-reactions
    b) The nature of the electrodes and the electrolyte determine the oxidation and reduction reactions which occur
    c) Inert electrodes, such as graphite and platinum, are made from substances which conduct electricity and are not chemically altered in cell reactions.
    d) The labeling of the electrodes as anode or cathode depends on the site of the oxidation and reduction half-reactions. The electrode at which oxidation occurs is called the anode while the electrode at which reduction occurs is called the cathode.
    e) The anode is labeled (–) while the cathode is labeled (+).

4. Transfer of charge
    a) If the anode is oxidized, electrons move directly from the anode to the cathode through the external circuit and positive ions are released into solution around

the anode as it dissolves. At the cathode the substance being reduced accepts electrons.

b) If the anode does not react, electrons are transferred directly from the oxidized substance onto the anode and then through the external circuit to the cathode. At the cathode the substance being reduced accepts electrons.
c) An electrolyte conducts electricity within a cell by the movement of dissolved positively and negatively charged ions. The movement of ions completes the circuit and maintains electrical neutrality.
d) Negative ions are called anions and positive ions are called cations.
e) Anions move through the electrolyte to the anode and cations move to the cathode
f) A salt bridge contains ions in solution and provides a continuous path for the movement of ions between separate half-cells.

5. Reduction potentials, standard reduction potentials, and standard reduction potential tables.
   a) Reduction potentials indicate the relative tendency of substances to be reduced and on a reduction potential table, are listed by half-reaction equations in order of decreasing tendency to be reduced (decreasing strength as oxidizing agents).
   b) Standard reduction potentials are determined in relation to the $2\ H^+_{(aq)} + 2\ e^- \rightarrow H_{2(g)}$ half cell reaction which is assigned an E° of 0 V. Substances more readily reduced than hydrogen ions are listed above hydrogen and have positive E° values while those which are more difficult to reduce are listed below and have negative E° values.
   c) Standard reduction potentials assume conditions of 1.0 mol/L concentration, 101.3 kPa pressure and usually 25 °C temperature.
   d) Standard reduction potentials can be read as standard oxidation potentials if the sign of the E° is changed and the equation is read in the reverse direction (from right to left).
   e) Standard reduction potential tables list oxidizing agents in decreasing strength from the top to the bottom on the left side of the table and reducing agents in decreasing strength from the bottom to the top on the right side of the table.
   f) Standard reduction potential tables can be used to predict whether or not oxidation-reduction reactions are likely to occur, either in a cell or by the direct mixing of reagents.
   g) Standard reduction potential tables can be used to predict the oxidation and reduction half-reactions that may occur at the anode and cathode, and the equations for the half-reactions can be combined to determine the net cell reaction and equation.
   h) Standard reduction potential tables can be used to predict the site of the anode and cathode in an electrochemical cell.
   i) Standard reduction potential tables can be used to predict the cell potential of a voltaic cell. (Predictions should be interpreted with caution since they provide no information about the rate of the reaction, the concentration of the reaction species or other factors which affect reduction potentials.)

Electrolytic cells

6. In an electrolytic cell:
   a) electrical energy is used from an external power source to produce a chemical change
   b) the reactants will not react if mixed but the products will react if mixed
   c) a potential applied across the electrodes forces an oxidation-reduction reaction to occur at the electrodes
   d) the applied potential must be greater than the predicted cell potential and in the opposite direction

7. Electrodes
   a) Electrodes are electrical conductors which are placed in an electrolyte to provide surfaces for oxidation and reduction half-reactions.
   b) The nature of the electrodes and the electrolyte determine the oxidation and reduction reactions that occur.
   c) Inert electrodes, such as graphite and platinum, are made from substances which conduct electricity and are not chemically altered in cell reactions.
   d) The anode and the cathode are determined by the connection of the terminals of the external power source and the subsequent direction of electron flow. The electrode connected to the positive terminal of the power source becomes the anode and the electrode connected to the negative terminal becomes the cathode.
   e) The anode is the electrode at which oxidation occurs while the cathode is the electrode at which reduction occurs.
   f) The anode is labeled (+) and the cathode is labeled (–).

8. Transfer of charge
   a) In the external circuit, electrons travel from the negative terminal of the power source to the cathode and from the anode to the positive terminal of the power source
   b) In the internal circuit, the movement of ions maintains electrical neutrality and completes the circuit.
   c) An electrolyte conducts electricity within a cell by the movement of dissolved positively and negatively charged ions. The movement of ions completes the circuit and maintains electrical neutrality.
   d) Negative ions are called anions and positive ions are called cations.
   e) Anions move through the electrolyte to the anode and cations move to the cathode.

9. Electrolytic cell reactions and standard reduction potential tables
   a) The half-reaction at the cathode results from the reduction of cations (in molten or aqueous solution), or the reduction of water (in solution) to form hydrogen gas and hydroxide ions.

b) The half-reaction at the anode results from the oxidation of the metal electrode or anions (in molten or aqueous solution), or water (in solution) to form oxygen gas and hydrogen ions.
c) The cell reaction may be predicted from the tables of reduction potentials by combining anode and cathode half-reactions.
d) The cell reaction requiring the lowest potential occurs first.
e) The cell potential predicted from tables of standard reduction potentials is negative and indicates that the reactions will occur with an applied power source.
f) For a reaction to take place, the applied potential must be greater than the predicted negative cell potential.
g) The concentration of reactants, nature of the electrodes and electrolyte, and other factors determine which cell reactions occur. (Other factors include temperature, pressure, polarization, and overpotential effects).

Appendix B: Pilot study diagnostic instrument

Chemistry 30

Electrochemistry Diagnostic Instrument – Pilot

Description

Time: 60 min

This is a **closed-book** test, consisting of 18 questions. There are 6 pairs of questions which must be answered together and 6 questions with an open response.

Types of questions:

- Paired questions - the second question is based on the reason that you chose your answer to the first question.
- Open-response questions – provide a written reason why you chose your answer in the previous question.

Include all of your work in the booklet. No scrap paper is provided.

Please transfer your answers to the answer sheet provided.

A chemistry data booklet is provided for your reference.

Student Version

Use the following standard electrode potentials to answer the next two questions.

Reduction Half-Reaction	Electrical Potential (V)
1 $X^{3+}_{(aq)} + 3\ e^- \rightarrow X_{(s)}$ 5	+1.95
2 $Q_{(l)} + e^- \rightarrow Q^-_{(aq)}$ 6	+0.61
3 $Y^{2+}_{(aq)} + e^- \rightarrow Y^+_{(aq)}$ 7	+0.02
4 $M_{(s)} + 3\ e^- \rightarrow M^{3+}_{(aq)}$ 8	−0.25

1-1. Which of the following tables identifies, with checkmarks (✓), the spontaneous reactions that would be predicted given the half-reactions shown above?

A.

	$X_{(s)}$	$Q^-_{(aq)}$	$Y^+_{(aq)}$	$M^{3-}_{(aq)}$
$X^{3+}_{(aq)}$	-	-	-	-
$Q_{(l)}$	✓	-	-	-
$Y^{2+}_{(aq)}$	✓	✓	-	✓
$M_{(s)}$	✓	✓	-	-

B.

	$X_{(s)}$	$Q^-_{(aq)}$	$Y^+_{(aq)}$	$M^{3-}_{(aq)}$
$X^{3+}_{(aq)}$	-	✓	✓	✓
$Q_{(l)}$	-	-	✓	✓
$Y^{2+}_{(aq)}$	-	-	-	✓
$M_{(s)}$	-	-	-	-

C.

	$X_{(s)}$	$Q^-_{(aq)}$	$Y^+_{(aq)}$	$M^{3-}_{(aq)}$
$X^{3+}_{(aq)}$	✓	✓	✓	-
$Q_{(l)}$	✓	✓	-	-
$Y^{2+}_{(aq)}$	✓	-	-	-
$M_{(s)}$	-	-	-	-

D.

	$X_{(s)}$	$Q^-_{(aq)}$	$Y^+_{(aq)}$	$M^{3-}_{(aq)}$
$X^{3+}_{(aq)}$	-	✓	✓	✓
$Q_{(l)}$	-	✓	✓	-
$Y^{2+}_{(aq)}$	-	✓	-	-
$M_{(s)}$	-	-	-	-

Numerical Response

1-2. Identify the number beside the species from the standard reduction potential table above that applies to each descriptor below.

The strongest oxidizing agent ________ (Record in the **first** column)
The weakest reducing agent ________ (Record in the **second** column)
The greatest tendency to be reduced ________ (Record in the **third** column)
The least tendency to be oxidized ________ (Record in the **fourth** column)

2-1. The half-reaction to which all other half-cell potentials are compared is

A. $Li^+_{(aq)} + e^- \rightarrow Li_{(s)}$

B. $F_{2(g)} + 2\ e^- \rightarrow 2\,F^-_{(aq)}$

C. $2\,H^+_{(aq)} + 2\ e^- \rightarrow H_{2(g)}$

D. $Au^{3+}_{(aq)} + 3\ e^- \rightarrow Au_{(s)}$

2-2. The reason why a standard half-cell is used is that

A. the designation of 0 V for the standard half-cell is arbitrary

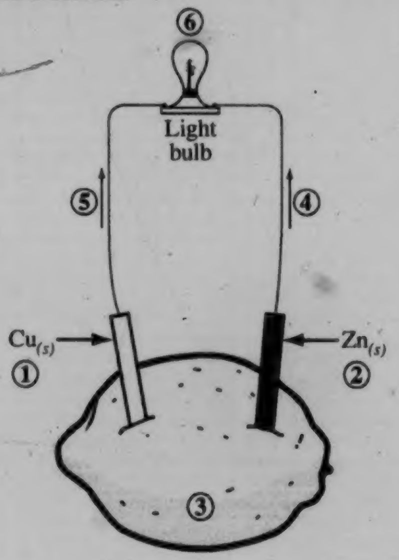
B. the reduction potential of a half-cell can be used to predict the spontaneity of individual half cells

C. the designation of the standard half-cell is based on the chemistry of the components that make up the half-cell

D. all half reactions that are listed above the standard half on a table of reduction half reaction will be spontaneous.

Use the following information to answer the next two questions.

A voltaic cell capable of lighting a small light bulb can be made by placing copper and zinc strips in a lemon.



Numerical Response

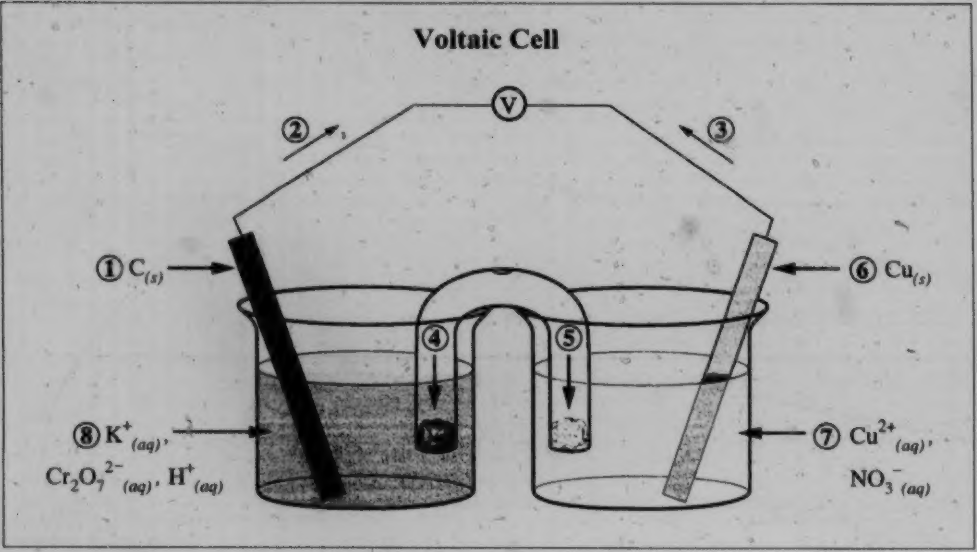
3-1. Identify the part of the voltaic cell, as numbered above, that corresponds to each of the descriptors listed below.

Anode __________ (Record in the **first** column)
Cathode __________ (Record in the **second** column)
Electron flow __________ (Record in the **third** column)
Electrolyte __________ (Record in the **fourth** column)

3-2. The anode in the electrochemical cell above is

A. identified by its location in the cell
B. the species with the highest reduction potential
C. the metal with the least ability to attract electrons
D. the metal that is listed highest in the standard reduction potential table

Use the following diagram to answer the next two questions.



Voltaic Cell

V
②
③
① $C_{(s)}$
⑥ $Cu_{(s)}$
④
⑤
⑧ $K^+_{(aq)}$, $Cr_2O_7^{2-}{}_{(aq)}$, $H^+_{(aq)}$
⑦ $Cu^{2+}_{(aq)}$, $NO_3^-{}_{(aq)}$

Numerical Response

4-1. In the diagram above, the number that represents the

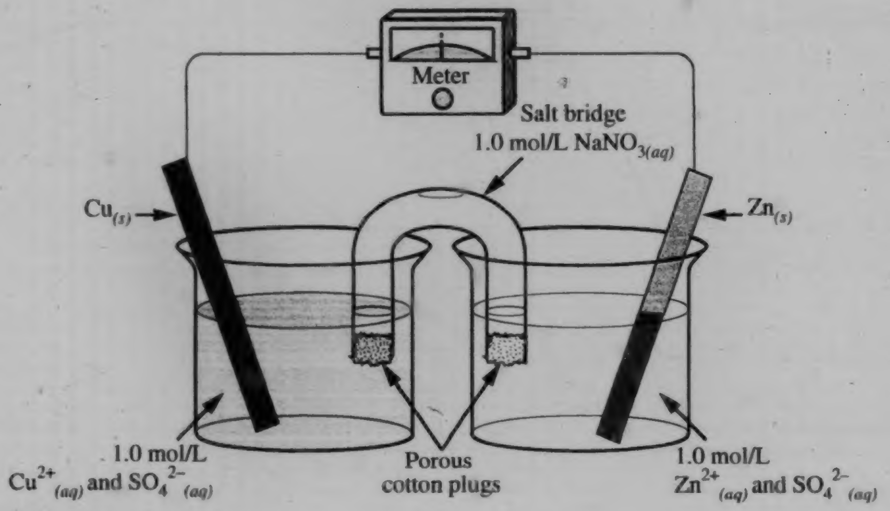
anode is __________ (Record in the **first** column)
cathode is __________ (Record in the **second** column)
cation flow is __________ (Record in the **third** column)
electron flow is __________ (Record in the **fourth** column)

4-2. Which of the following statements applies to the electrochemical cell in the diagram above?

A. Protons are attracted to the anode because it is negatively charged.
B. Electrons are attracted to the cathode because it is positively charged.
C. Cations move towards the cathode so that the cell remains electrically neutral.
D. Cations are attracted to anions in the electrolyte which limits their movement toward the cathode.

Use the following information to answer the next two questions.

Electrochemical Cell


Meter
Salt bridge
1.0 mol/L $NaNO_{3(aq)}$
$Cu_{(s)}$
$Zn_{(s)}$
1.0 mol/L
$Cu^{2+}{}_{(aq)}$ and $SO_4{}^{2-}{}_{(aq)}$
Porous
cotton plugs
1.0 mol/L
$Zn^{2+}{}_{(aq)}$ and $SO_4{}^{2-}{}_{(aq)}$

Numerical Response

5-1. A student attempted to replicate a traditional Daniell Cell by setting up the electrochemical cell shown above. Under standard conditions, the electrical potential of the cell should be +/– __________ V.

(Record your **three-digit answer** in the numerical-response section on the answer sheet.)

5-2. In the electrochemical cell above electrons move through the

A. electrolyte because they are attracted to the positive ions in the solution

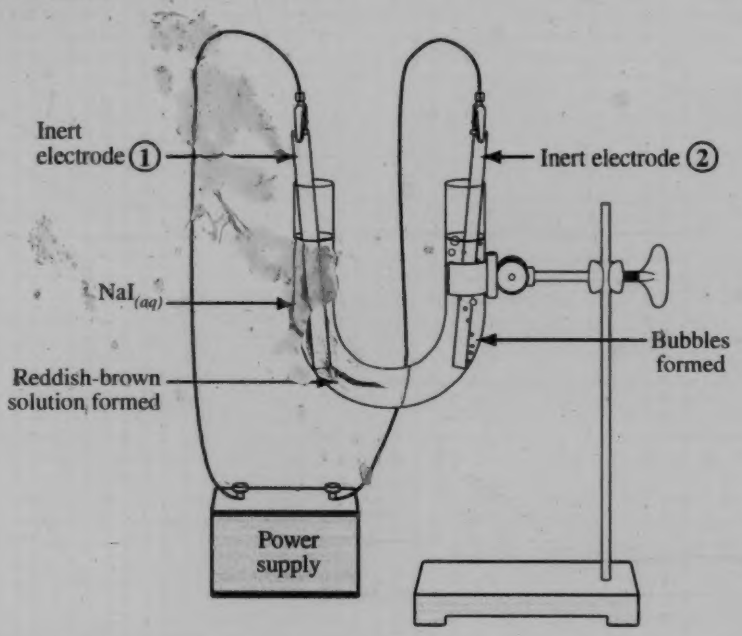
B. electrolyte in one direction and protons move through the electrolyte in the opposite direction

C. wire from the electrode with the lower reduction potential to the electrode with the higher reduction potential

D. wire from the electrode with the high concentration of electrons to the electrode with the low concentration of electrons

Use the following information to answer the next two questions.

A student set up the following electrochemical cell and allowed it to operate for a few minutes.


Inert electrode ①
Inert electrode ②
NaI(aq)
Bubbles formed
Reddish-brown solution formed
Power supply

6-1. The gas formed near electrode 2 is **most likely**

A. $I_{2(g)}$

B. $Na_{(g)}$

C. $O_{2(g)}$

D. $H_{2(g)}$

6-2. Which of the following statements applies to the electrochemical cell in the diagram above?

A. The same reaction occurs at each of the inert electrodes.

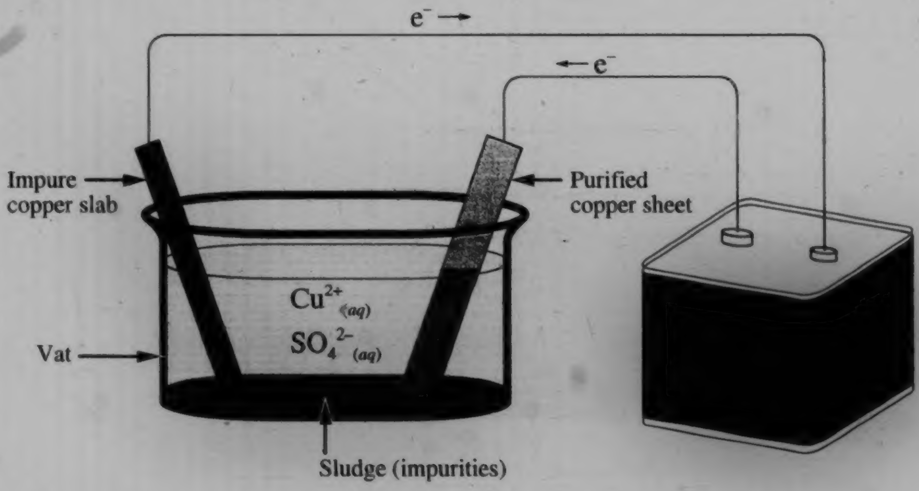
B. The inert electrodes are oxidized and reduced in this cell.

C. Water does not react during the electrolysis of aqueous solutions.

D. The chemical reactions occur on the surface of the inert electrodes.

Use the following information to answer the next question.

Copper can be refined (purified) using an apparatus like the one shown below, which is a small-scale version of an industrial apparatus.


e⁻ →
← e⁻
Impure copper slab
Purified copper sheet
Cu²⁺(aq)
SO₄²⁻(aq)
Vat
Sludge (impurities)

Numerical Response

7. If the direct current power supply produces a steady 3.50 A current, then the time required to deposit 0.100 g of purified copper is __________ s.

The reason for your choice in the question above is

____

____

Use the following information to answer the next question.

A student used an acidified 6.31×10^{-2} mol/L $KMnO_{4(aq)}$ solution to titrate 25.0 mL samples of $Fe^{2+}{}_{(aq)}$ solution of unknown concentration. In the reactions, the $Fe^{2+}{}_{(aq)}$ ion was oxidized to the $Fe^{3+}{}_{(aq)}$ ion. The student completed five trials and summarized the data in a table.

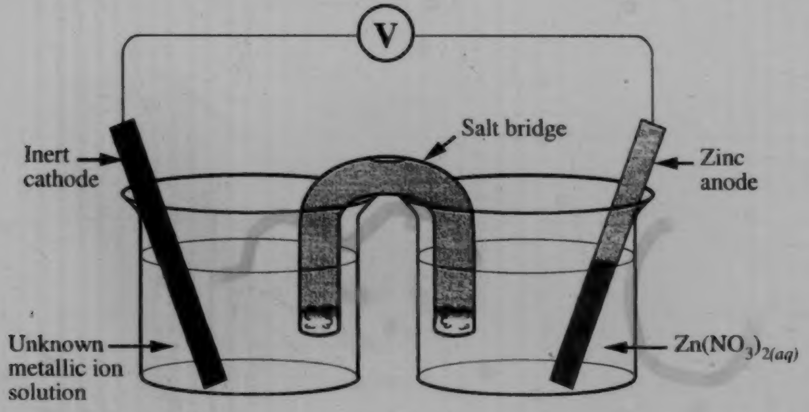
Trial Number	**1**	**2**	**3**	**4**	**5**
Final Buret Reading (mL)	17.55	35.65	26.40	42.65	16.85
Initial Buret Reading (mL)	0.30	17.55	10.05	26.40	0.55
Final Colour	purple	purple	pink	pink	pink

8. According to the student's data, the concentration of $Fe^{2+}{}_{(aq)}$ is

A. 0.206 mol/L
B. 0.213 mol/L
C. 0.218 mol/L
D. 0.223 mol/L

The reason for your choice in the question above is

To determine the identity of an unknown metallic ion in a solution, a student designed the voltaic cell shown below.


V
Salt bridge
Inert cathode
Zinc anode
Unknown metallic ion solution
$Zn(NO_3)_{2(aq)}$

Numerical Response

9. If the charge on the unidentified metal ion is 3+, then the number of moles of the metal produced when the zinc anode decreases in mass by 200 g is __________ mol.

The reason for your choice in the question above is

___

___

10. Which of the following is a correct statement about the oxidation state of an atom?

A. The oxidation number of oxygen in $O_{2(g)}$ is 0
B. The oxidation number of chlorine in $Cl_{2(g)}$ is -1
C. The oxidation number of sulfur in $SO_4^{2-}{}_{(aq)}$ is -2
D. The oxidation number of phosphorus in $Na_3PO_{4(aq)}$ is -3

The reason for your choice in the question above is

Use the following equations to answer the next question.

1 $Fe^{2+}{}_{(aq)} + Cr^{3+}{}_{(aq)} \rightarrow Fe^{3+}{}_{(aq)} + Cr^{2+}{}_{(aq)}$
2 $NH_{3(aq)} + H_2O_{(l)} \rightarrow NH_4^{+}{}_{(aq)} + OH^{-}{}_{(aq)}$
3 $2\,NH_{3(l)} + \frac{7}{2}O_{2(g)} \rightarrow 2\,NO_{2(g)} + 3\,H_2O_{(g)}$
4 $Mg^{2+}{}_{(aq)} + 2\,OH^{-}{}_{(aq)} \rightarrow Mg(OH)_{2(s)}$
5 $Sn^{2+}{}_{(aq)} + 2\,NO_3^{-}{}_{(aq)} + 4\,H^{+}{}_{(aq)} \rightarrow Sn^{4+}{}_{(aq)} + 2\,NO_{2(g)} + 2\,H_2O_{(l)}$
6 $PbSO_{4(s)} + SO_3^{2-}{}_{(aq)} + 2\,OH^{-}{}_{(aq)} \rightarrow H_2O_{(l)} + Pb_{(s)} + 2\,SO_4^{2-}{}_{(aq)}$

Numerical Response

11. The equations that represent oxidation–reduction reactions, listed in any order, are _____, _____, _____, and _____.

The reason for your choice in the question above is

Use the following information to answer the next question.

Common household bleach is an aqueous solution that contains approximately 5% sodium hypochlorite. The equilibrium involved in the production of bleach from chlorine can be represented by the reaction equation

$$Cl_{2(g)} + 2\,OH^-_{(aq)} \rightarrow ClO^-_{(aq)} + Cl^-_{(aq)} + H_2O_{(l)}$$

12. In the production of bleach, the reduction half-reaction is

A. $Cl_{2(g)} + 2\,e^- \rightarrow 2\,Cl^-_{(aq)}$

B. $2\,Cl^-_{(aq)} \rightarrow Cl_{2(g)} + 2\,e^-$

C. $4\,OH^-_{(aq)} \rightarrow O_{2(g)} + 2\,H_2O_{(l)} + 4\,e^-$

D. $ClO^-_{(aq)} + H_2O_{(l)} + 2\,e^- \rightarrow Cl^-_{(aq)} + 2\,OH^-_{(aq)}$

The reason for your choice in the question above is

____

____

Appendix C: Main study diagnostic instrument

Chemistry 30

Electrochemistry Diagnostic Instrument

Description

Time: 60 min

This is a **closed-book** test, consisting of 20 questions. There are 10 pairs of questions that were designed to be answered together. The second question is based on the reason that you chose your answer to the first question in the pair.

Include all of your work in the booklet. No scrap paper is provided.

Please transfer your answers to the answer sheet provided.

A chemistry data booklet is provided for your reference.

Student Version

1-1. The half-reaction to which all other half-cell reduction potentials are compared is

A. $Li^+_{(aq)} + e^- \rightarrow Li_{(s)}$

B. $F_{2(g)} + 2\,e^- \rightarrow 2\,F^-_{(aq)}$

C. $2\,H^+_{(aq)} + 2\,e^- \rightarrow H_{2(g)}$

D. $Au^{3+}_{(aq)} + 3\,e^- \rightarrow Au_{(s)}$

1-2. Which of the following statements explains why a standard half-cell is used?

A. The designation of 0 V for the standard half-cell is arbitrary.

B. The hydrogen half-cell is the only reduction half-reaction that produces 0 V.

C. All half reactions that are listed above the standard half on a table of reduction half reaction will be spontaneous.

D. The designation of the standard half-cell is based on the chemistry of the components that make up the half-cell.

Use the following information to answer the next two questions.

Standard Electrode Potentials

$VO_2{}^{+}{}_{(aq)} + 2\,H^{+}{}_{(aq)} + e^{-} \rightarrow VO^{2+}{}_{(aq)} + H_2O_{(l)}$	$E° = +0.999$ V
$VO^{2+}{}_{(aq)} + 2\,H^{+}{}_{(aq)} + e^{-} \rightarrow V^{3+}{}_{(aq)} + H_2O_{(l)}$	$E° = +0.340$ V
$VO_2{}^{+}{}_{(aq)} + 4\,H^{+}{}_{(aq)} + 5\,e^{-} \rightarrow V_{(s)} + 2\,H_2O_{(l)}$	$E° = -0.250$ V
$V^{3+}{}_{(aq)} + e^{-} \rightarrow V^{2+}{}_{(aq)}$	$E° = -0.255$ V

2-1. Which of the following substances is the strongest reducing agent?

A. $V^{2+}{}_{(aq)}$
B. $V^{3+}{}_{(aq)}$
C. $VO_2{}^{+}{}_{(aq)}$
D. $VO^{2+}{}_{(aq)}$

2-2. Which of the following statements applies to the standard electrode potential table above?

A. A half-reaction with a negative reduction potential will be nonspontaneous.

B. Cell potentials are determined by adding the reduction potentials from the standard electrode potential table.

C. In a standard reduction potential table, reducing agents are listed in order of decreasing reactivity from the top of the table to the bottom of the table.

D. In a standard reduction potential table, species are listed in order of decreasing tendency to attract electrons from the top of the table to the bottom of the table.

Use the following information to answer the next two questions.

$$U^{3+}{}_{(aq)} + La_{(s)} \rightarrow La^{3+}{}_{(aq)} + U_{(s)}$$

$$Y^{3+}{}_{(aq)} + U_{(s)} \rightarrow \text{no reaction}$$

$$Y^{3+}{}_{(aq)} + La_{(s)} \rightarrow La^{3+}{}_{(aq)} + Y_{(s)}$$

3-1. Which of the following statements applies to the equations above?

A. The oxidizing agent loses electrons.
B. The reducing agent undergoes reduction.
C. The oxidation number increases in the species undergoing reduction.
D. Electrons are transferred from the reducing agent to the oxidizing agent.

3-2. The oxidizing agents above, listed from strongest to weakest, are

A. $U_{(s)}$, $Y_{(s)}$, $La_{(s)}$
B. $U^{3+}{}_{(aq)}$, $Y^{3+}{}_{(aq)}$, $La^{3+}{}_{(aq)}$
C. $U^{3+}{}_{(aq)}$, $La^{3+}{}_{(aq)}$, $Y^{3+}{}_{(aq)}$
D. $Y^{3+}{}_{(aq)}$, $U^{3+}{}_{(aq)}$, $La^{3+}{}_{(aq)}$

Use the following information to answer the next two questions.

1 $H_{2(g)} + Cl_{2(g)} \rightarrow 2\,HCl_{(g)}$
2 $SO_{3(g)} + H_2O_{(l)} \rightarrow H_2SO_{4(aq)}$
3 $NH_{3(aq)} + H_2O_{(l)} \rightarrow NH_4{}^{+}{}_{(aq)} + OH^{-}{}_{(aq)}$
4 $2\,NH_{3(g)} + \tfrac{1}{2}\,O_{2(g)} \rightarrow 2\,NO_{2(g)} + 3\,H_2O_{(g)}$

4-1. Which of the following is a correct statement about the oxidation state of an atom?

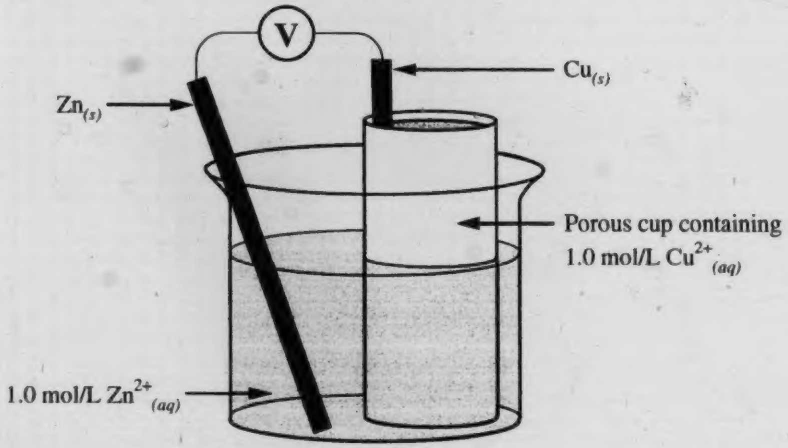
A. The oxidation number of oxygen in $O_{2(g)}$ is 0.
B. The oxidation number of chlorine in $Cl_{2(g)}$ is -1.
C. The oxidation number of nitrogen in $NH_4{}^{+}{}_{(aq)}$ is $+1$.
D. The oxidation number of sulfur in $H_2SO_{4(aq)}$ is -2.

4-2. Which of the equations above represent redox reactions?

A. 3 only
B. 4 only
C. 1 and 4
D. 2, 3 and 4

Use the following information to answer the next two questions.

Electrochemical Cell


V
$Cu_{(s)}$
$Zn_{(s)}$
Porous cup containing 1.0 mol/L $Cu^{2+}_{(aq)}$
1.0 mol/L $Zn^{2+}_{(aq)}$

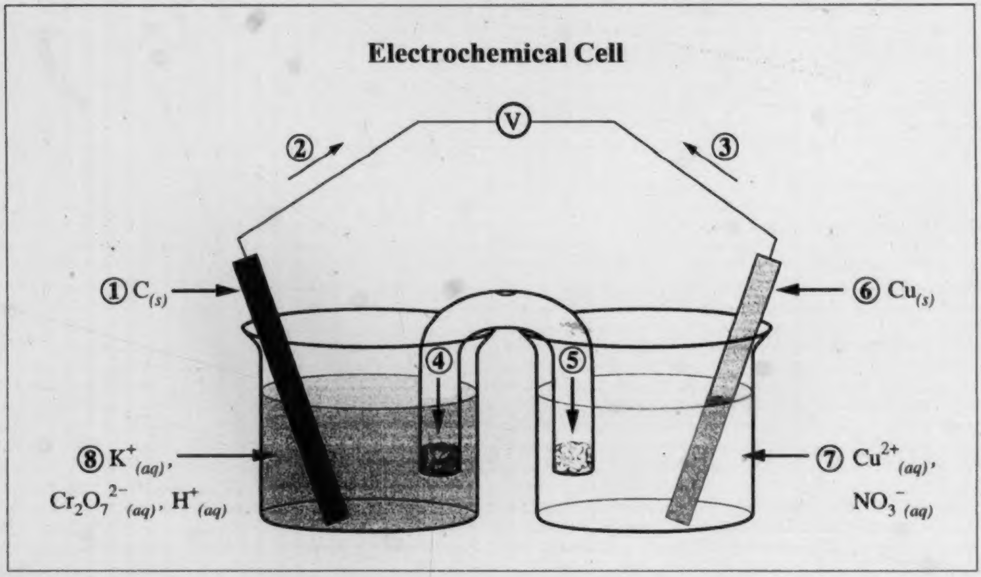
5-1. The cell potential for the electrochemical cell in the diagram above is

A. +1.10 V
B. +0.42 V
C. –0.42 V
D. –1.10 V

5-2. In the electrochemical cell above electrons move through the

A. electrolyte because they are attracted to the positive ions in the solution
B. electrolyte in one direction and protons move through the electrolyte in the opposite direction
C. wire from the electrode with the lower reduction potential to the electrode with the higher reduction potential
D. wire from the electrode with the high concentration of electrons to the electrode with the low concentration of electrons

Use the following information to answer the next two questions.



Electrochemical Cell

V
②
③
① $C_{(s)}$
④
⑤
⑥ $Cu_{(s)}$
⑧ $K^+_{(aq)}$, $Cr_2O_7^{2-}{}_{(aq)}$, $H^+_{(aq)}$
⑦ $Cu^{2+}_{(aq)}$, $NO_3^-{}_{(aq)}$

6-1. Which of the following statements applies to the electrochemical cell above?

A. The anode is labelled 1.

B. Electron flow is labelled 2.

C. Cation movement is labelled 4.

D. The strongest reducing agent is $Cr_2O_7^{2-}{}_{(aq)}$ and $H^+_{(aq)}$.

6-2. Which of the following statements applies to the electrochemical cell above?

A. Protons are attracted to the anode because it is negatively charged.

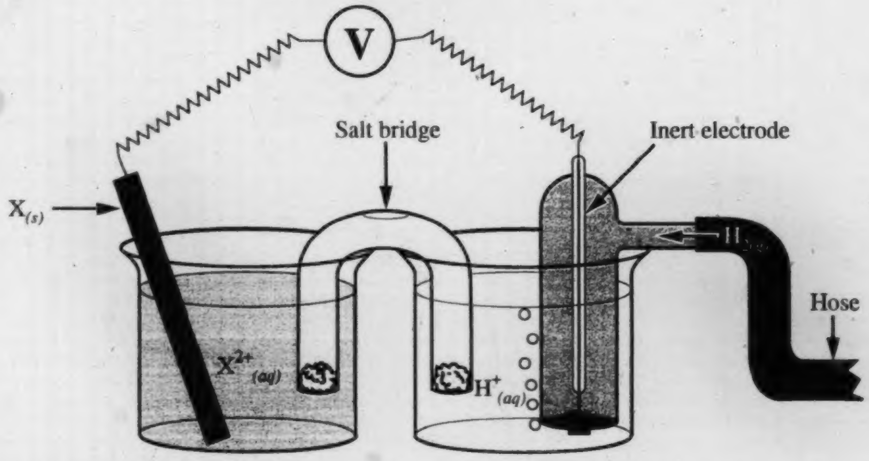
B. Electrons are attracted to the cathode because it is positively charged.

C. Cations move towards the cathode so that the cell remains electrically neutral.

D. Cations are attracted to anions in the electrolyte which limits their movement toward the cathode.

Use the following information to answer the next two questions.

Electrochemical Cell



In this apparatus, the anions in the solution move from the hydrogen half-cell solution into the salt bridge and migrate toward the $X_{(s)}$ electrode.

7-1. If the voltmeter reads +0.40 V under standard conditions, then $X_{(s)}$ is most likely

A. $Ag_{(s)}$

B. $Al_{(s)}$

C. $Cd_{(s)}$

D. $O_{2(g)} + H_2O_{(l)}$

7-2. Which of the following statements describe the circuit in the electrochemical cell above?

A. The salt bridge supplies electrons to complete the circuit.

B. An operating circuit requires the movement of anions, cations and electrons.

C. Electrons enter the electrolyte at the cathode, move through the electrolyte, and emerge at the anode.

D. The salt bridge assists the flow of electrons because positive ions in the bridge attract electrons from one half-cell to the other half-cell.

Use the following information to answer the next two questions.

An electrolytic cell is used to produce molten aluminum from molten aluminum oxide, as represented by the simplified equation below.

$$2\,Al_2O_{3(l)} \rightarrow 4\,Al_{(l)} + 3\,O_{2(g)}$$

8-1. Which of the following equations represents the reduction half-reaction when molten aluminum oxide undergoes electrolysis?

A. $2\,O^{2-}{}_{(l)} + 4\,e^- \rightarrow O_{2(g)}$

B. $2\,O^{2-}{}_{(l)} \rightarrow O_{2(g)} + 4\,e^-$

C. $Al^{3+}{}_{(l)} \rightarrow Al_{(l)} + 3\,e^-$

D. $Al^{3+}{}_{(l)} + 3\,e^- \rightarrow Al_{(l)}$

8-2. If 50 000 A were applied to the electrolytic cell for 5.00 h, then the mass of aluminum produced would be

A. 9.33×10^3 g

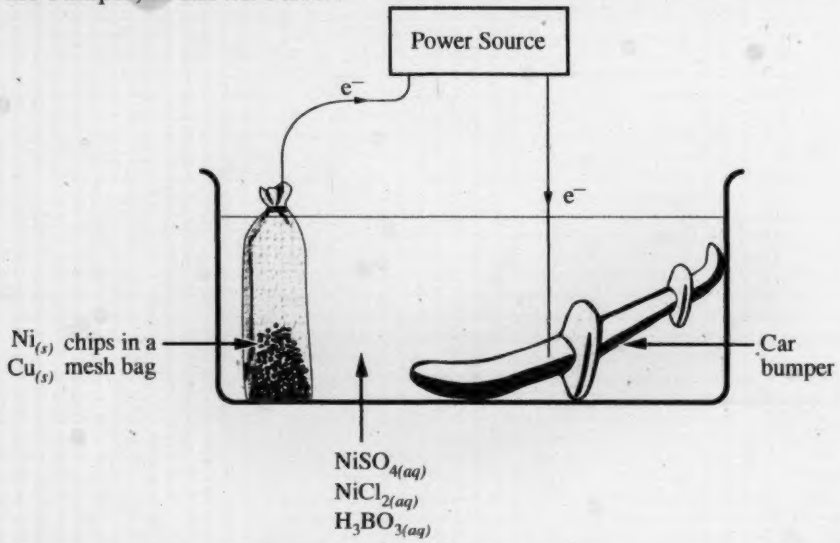
B. 8.39×10^4 g

C. 2.52×10^5 g

D. 7.55×10^5 g

Use the following information to answer the next two questions.

In order to refinish a car bumper, the first step is to clean the bumper and repair any damaged areas. The second step is the electroplating of nickel on the bumper, as shown below.



9-1. *The plating of the car bumper will take place at the ___i___ where ___ii___ occurs.*

The statement above is completed by the information in row

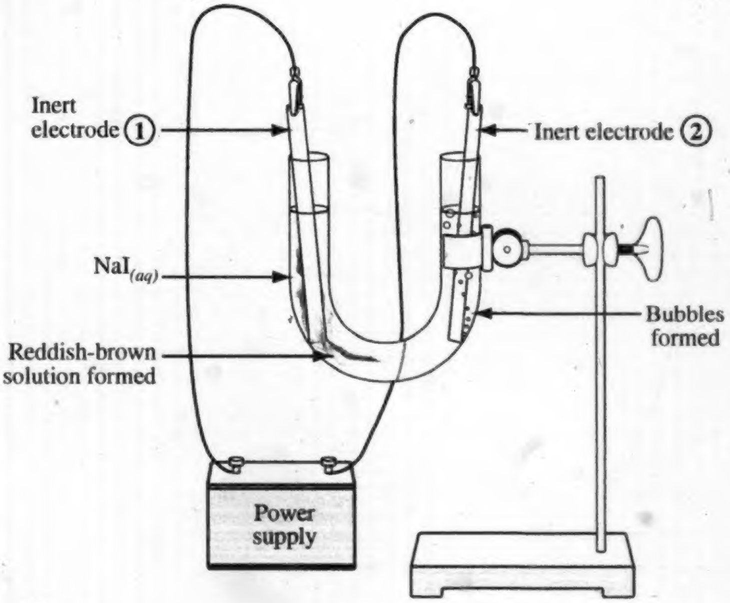
Row	*i*	*ii*
A.	anode	oxidation
B.	anode	reduction
C.	cathode	oxidation
D.	cathode	reduction

9-2. The anode in the electrochemical cell above is

A. identified by its location in the cell
B. the species with the highest reduction potential
C. the metal with the least ability to attract electrons
D. the electrode with the highest concentration of electrons

Use the following information to answer the next two questions.

A student set up the following electrochemical cell and allowed it to operate for a few minutes.


Inert electrode ①
Inert electrode ②
NaI(aq)
Bubbles formed
Reddish-brown solution formed
Power supply

10-1. The gas formed near electrode 2 is **most likely**

- **A.** $I_{2(g)}$
- **B.** $Na_{(g)}$
- **C.** $O_{2(g)}$
- **D.** $H_{2(g)}$

10-2. Which of the following statements applies to the electrochemical cell in the diagram above?

- **A.** The same reaction occurs at each of the inert electrodes.
- **B.** The inert electrodes are oxidized and reduced in this cell.
- **C.** Water does not react during the electrolysis of aqueous solutions.
- **D.** The chemical reactions occur on the surface of the inert electrodes.

Appendix D: Alternative conceptions in electrochemistry

Table D-1. Alternative conceptions for electric circuits and electric current concepts

Alternative Conception	Source
1a. In a cell the anions and cations attract each other and this affects the movement of ions to the electrodes.	Garnett & Treagust, 1992a
1b. Electrons move through electrolytes by being attracted to positive ions in solution.	Garnett & Treagust, 1992a
1c. Electrons move through the electrolytes by being transported by negative ions in solution.	O'Grady-Morris, unpublished data
2a. Protons flow in metallic conductors.	Garnett & Treagust, 1992a
2b. Conventional current is the flow of positive charges (usually protons).	Garnett & Treagust, 1992a
2c. Electricity in chemistry and physics is different because the current flows in opposite directions.	Garnett & Treagust, 1992a
2d. Protons flow in electrolytes (regardless of whether the solution is acidic, basic or neutral).	Garnett & Treagust, 1992a
2e. Electrons flow in electrolytes.	Garnett & Treagust, 1992a
2f. Protons and electrons flow in opposite direction in an electrolyte.	Garnett & Treagust, 1992a
2g. The movement of ions in solution does not constitute and electric current.	Garnett & Treagust, 1992a
2h. Electrons move through solution by being attracted from one ion to another.	Garnett & Treagust, 1992a
2i. When an electrolyte conducts a current, electrons move onto an ion at the cathode and are carried by that ion to the anode.	Garnett & Treagust, 1992a
2j. Electron repulsion in the anode forces electrons to move from the anode into the connecting wires	O'Grady-Morris, unpublished data
2k. Anions move because of repulsion by anions	O'Grady-Morris, unpublished data

Table D-2. Alternative conceptions for cell potential concepts

Alternative Conception	Source
14a. Cell potentials are derived by adding individual reduction potentials.	Sanger & Greenbowe, 1997b
14b. Half-cell potentials are not intensive properties	Sanger & Greenbowe, 1997b

Table D-3. Alternative conceptions for oxidation and reduction concepts

Assigning oxidation states
4a. The oxidation state of an element is the same as the charge of the monatomic ion of that element.
4b. Oxidation numbers or states can be assigned to polyatomic molecules and/or polyatomic ions.
4c. The charge of a polyatomic species indicates the oxidation state of the molecule or ion.
Identifying oxidation-reduction equations using oxidation numbers
5a. In an equation, changes in charges of polyatomic species can be used to identify redox equations.
5b. In an equation, changes in the charges of polyatomic species can be used to determine the number of electrons removed from, or gained by, reacting species.
Using other definitions to identify oxidation-reduction equations
6. In all chemical equations, the definitions of oxidation as the addition of oxygen and reduction as the removal of oxygen can be used to identify oxidation and reduction.
The interdependence of oxidation and reduction processes
7. Oxidation and reduction processes can occur independently.

From: Garnett & Treagust, 1992a.

Table D-4. Alternative conceptions for voltaic cells

Alternative Conception	Source
Identifying the anode and cathode in electrochemical cells	
8a. In standard reduction potential tables the species with the highest E° value is the anode.	Garnett & Treagust, 1992b
8b. Standard reduction potential tables list metals in order of decreasing reactivity from the top down.	Garnett & Treagust, 1992b
8c. The identity of the anode and cathode depends on the physical placement of the half-cells.	Sanger & Greenbowe, 1997b
8d. Anodes, like anions, are always negatively charged; cathodes, like cations, are always positively charged.	Sanger & Greenbowe, 1997b
The need for a standard half-cell	
9a. The designation of the E° for the H_2 (1M / H^+ standard half-cell is not arbitrary but based on the chemistry of H^+ and H_2.	Garnett & Treagust, 1992b
9b. The standard half-cell is not necessary.	Garnett & Treagust, 1992b
9c. Half-cell potentials are absolute in nature and can be used to predict the spontaneity of the half cells.	Sanger & Greenbowe, 1997b
9d. When an electrode is immersed into an electrolyte, an electrical double layer does not form at the interface between the electrolyte and the electrode immersed in it.	Ozkaya, 2002
Current in a voltaic cell	
10a. Electrons enter the electrolyte at the cathode, move through the electrolyte, and emerge at the anode.	Garnett & Treagust, 1992b
10b. The salt bridge supplies electrons to complete the circuit.	Garnett & Treagust, 1992b
10c. The salt bridge assists the flow of current (electrons) because positive ions in the bridge attract electrons from one half-cell to the other cell.	Garnett & Treagust, 1992b
10d. In an electrochemical cell the anions and cations move	Garnett & Treagust,

until their concentration in both half-cells is equal.	1992b
10e. Electrons can flow through aqueous solutions without assistance from the ions.	Sanger & Greenbowe, 1997a
10f. Only negatively charged ions constitute a flow of current in the electrolyte and the salt bridge.	Sanger & Greenbowe, 1997a
10g. Electrons can flow through the electrolyte in the absence of a salt bridge	O'Grady-Morris, unpublished data
The charge on the anode and cathode in electrochemical cells	
11a. The anode is negatively charged and because of this it attracts cations. The cathode is positively charged and because of this it attracts anions.	Garnett & Treagust, 1992b
11b. The anode is positively charged because it has lost electrons. The cathode is negatively charged because it has gained electrons.	Garnett & Treagust, 1992b
11c. The cathode is negatively charged and because of this it repels anions causing them to move away from the cathode and towards the anode	O'Grady-Morris, unpublished data

Table D-5. Alternative conceptions for electrolytic cells

Alternative Conception	**Source**
Identifying the anode and cathode	
12a. In and electrolytic cell the polarity of the terminals of the applied voltage has no effect on the site of the anode and cathode.	Garnett & Treagust, 1992b
12b. No reactions will occur at the surface of inert electrodes.	Garnett & Treagust, 1992b
12c. Processes at the anode and cathode are reversed in electrochemical and electrolytic cells; in electrochemical cells oxidation occurs at the anode and reduction at the cathode, while in electrolytic cells oxidation occurs at the cathode and reduction at the anode.	Garnett & Treagust, 1992b

12d. In electrolytic cells with identical electrodes connected to the battery, the same reactions will occur at each electrode.	Sanger & Greenbowe, 1997b
Predicting the products of electrolysis and the magnitude of the applied electromotive force (e.m.f.)	
13a. Water does not react during the electrolysis of aqueous solutions.	Garnett & Treagust, 1992b
13b. When predicting electrolytic cell reactions the oxidation and reduction half-equations from the standard reduction potential tables are reversed prior to combining them.	Garnett & Treagust, 1992b
13c. The predicted e.m.f. for an electrolytic cell may be positive.	Garnett & Treagust, 1992b
13d. There is no association between the calculated e.m.f. of an electrolytic cell and the magnitude if the applied voltage.	Garnett & Treagust, 1992b
13e. Inert electrodes can be oxidized or reduced.	Sanger & Greenbowe, 1997b
13f. When two or more oxidation or reduction half-reactions are possible, there is no way to determine which reaction will occur.	Sanger & Greenbowe, 1997b
13g. Electrolytic cells can force nonspontaneous reactions that do not involve electron transfer to happen.	Sanger & Greenbowe, 1997b
13h. Only one half-reaction occurs in an electrolytic cell because it occurs in one container.	O'Grady-Morris, unpublished data
13i. Ions do not move in an electrolytic cell because it occurs in one container.	O'Grady-Morris, unpublished data
13j. Only electrons and negatively charged ions constitute a flow of current in an electrolytic cell.	O'Grady-Morris, unpublished data
13k. Electrons flow through the electrolyte in an electrolytic cell because the salt bridge is absent	O'Grady-Morris, unpublished data
13l. Spontaneous reactions can be reversed by changing the	O'Grady-Morris,

direction of electron flow	unpublished data

Table D-6. Alternative conceptions for electrical neutrality in electrochemical cells

Alternative Conception	**Source**
18a. A cell can be electrically neutral when one half-cell is positive with cations only while the other half-cell is negative with an equal number of anions only.	Ogude & Bradley (1994)
18b. A cell can be electrically neutral with an unequal distribution of positive and negative ions as long as there are equal numbers of charges overall.	Ogude & Bradley (1994)
18c. The cell is electrically neutral because anions move towards the anode and react with cations produced during oxidation.	O'Grady-Morris, unpublished data
18d. As electrons are removed in the reduction reaction at the cathode, the negative charges are replaced by anions supplied from the salt bridge.	O'Grady-Morris, unpublished data
18e. The inert substance in the salt bridge neutralizes the electrolytes in the cell.	O'Grady-Morris, unpublished data
18f. Cations and anions move in opposite directions to equalize the concentration of charges in the cell.	O'Grady-Morris, unpublished data
18g. Cations move in both directions in the salt bridge to equalize the concentration of positive charges between the two half-cells.	O'Grady-Morris, unpublished data